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Computer simulation of the irrigation potential of selected low water holding capacity soils

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COMPUTER SIMULATION OF THE IRRIGATION POTENTIAL OF SELECTED LOW WATER HOLDING CAPACITY SOILS

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Computer simulation of the irrigation potential of selected low water holding capacity soils

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INTRODUCTION

In locations where agricultural drought is frequent, research on soil water-plant-weather relations can be conducted, and supplemental irrigation can be used to insure a range in plant moisture-stress conditions. In the Corn Belt, the climate is usually favorable for crop growth. However, short periods of drought are common because evaporation and actual crop water use during periods of dry weather are often greater than precipitation.

The purpose of this study is to evaluate the effect of irrigation on moisture stress and to determine how irrigation would affect the final yield by the removal of moisture stress on low moisture-holding-capacity soils. A soil-moisture computer program has been used to calculate a moisture stress index and predict corn yields. Evaporation, rainfall and soil moisture are inputs. An irrigation cycle is used in the program to estimate the response to irrigation.

The existing soil-moisture program also was modified in order to represent the condition that exists for a Cisne Soil in Fayette County, Illinois. The modified programs were run and moisture stress and excess indexes were calculated on the Cisne soil.

The irrigation of the coarse textured soils over selected areas in Iowa was also reviewed in order to measure the effect on the water resources. Sources of water supplies were evaluated to verify the practicality of irrigation.

LITERATURE REVIEW

As allocation of energy, water, and food supplies become more critical, it will become increasingly important to assess the frequency and degree of drought damage to crops and evaluate the needs for, and economics of, supplementing soil moisture for crop production. To do this, it is necessary to know for each stage of crop development the relation of soil water deficiency to crop growth and final yield, as well as the amount of water required by the crop for different soil-atmospheric regimes expected in an area.

The Effect of Soil Moisture Stress on the Development and Yield of Corn

Plant-water stress is caused by either excessive loss of water from the plant or an inadequate supply of water to the roots. Thus, the internal water balance of the plant is a function of both soil and atmospheric conditions (Slatyer, 1967). Kramer (1963) emphasizes that measurements of soil, water content, or soil-water potential are not sufficient to determine the effects of water supply on plant processes and yields. However, definite relations are most likely to exist between plant water potential and growth and yield of crops. Kramer (1969) states that "plant growth is controlled directly by plant-water stress and only indirectly by soil and atmospheric water stress."

The growth processes of cell division, vegetative and floral primordia initiation, and cell enlargement are sensitive to moisture stress. Cell division may continue at a reduced rate during moderate stress, although under severe stress the rate is drastically reduced (Slatyer, 1967). Loss of turgidity stops cell enlargement and results in smaller plants. Relatively small moisture stress sometimes produces a measurable reduction in growth (Van Barel, 1953; Kramer, 1963).

Time of moisture stress, in relation to the stage of crop development, has an important bearing on yield reduction. Claassen (1968) studied the water stress effect on development and yield components of corn. Reductions in yields due to stress were 53 percent when stress was applied near 75 percent silking and 29 percent when it was applied near 29 percent silking. Robins and Domingo (1953) reported that soil-moisture depletion to the wilting percentage by field corn at certain physiologic growth stages markedly depressed grain yields. Such deficits, for periods of one to two days during the tasseling or pollination period, resulted in as much as a 22 percent yield reduction, and periods of six to eight days gave a yield reduction of about 50 percent.

Denmead and Shaw (1960) investigated stress applied during three growth periods: vegetative, silking, and ear development. Stresses within each stage were applied by allowing the plants to deplete available soil moisture for three consecutive wetting and drying cycles, so that for a total of about eight days in the period, soil moisture was less than 50 percent of plant-available moisture capacity. They found that stress during any of these periods reduced yields below non-stress yields. However, a stress during the silking period reduced the yield by 51 percent. The reductions of yield at vegetative and ear stages were 25 and 21 percent, respectively. Most of the yield depression arising from vegetative period stress could be explained by reduced leaf area. Denmead and Shaw (1960) studied more specifically about the silking period and found a severe effect when water stress was imposed at 50 percent silking.

Claassen and Shaw (1970a, 1970b) imposed moisture stress on corn plants for a duration of four days, and nine different stages of growth, so that each experimental unit received only one stress treatment. Only slight yield reductions occurred if the degree of stress imposed in this study occurred during the vegetative growth period, except when the stress coincided with early earshoot and ovule development. Stresses imposed just prior to, and following 75 percent silking, caused more pronounced yield reductions. Stresses which occurred in the interval extending from the silking stage to dough stage also induced substantial yield depressions.

Miller and Duley (1925) obtained a 43 percent yield reduction by imposing a stress of 30 days beginning at early tasseling. Downey (1971) found a maximum decline in corn yield from water stress at the grain filling stage.

Runge (1968) concluded from his study of rainfall and temperature interactions on corn yield in Illinois that corn was sensitive to soil-moisture stress during a period before pollen shedding. Barnes and Woolley (1969) investigated the influence of moisture stresses at different stages of development for two hybrids; one with a tendency to produce two ears, and the other with a single-eared habit, but known to be highly susceptible to moisture deficiencies. Moisture stress during the silking and blister kernel stages reduced yields markedly for the single-eared hybrid. Only moderate yield reductions occurred in the double-eared hybrid from stresses imposed at the silking or blister kernel stages.

Crop Yield Response to Irrigation

Irrigation to improve or insure crop growth in humid areas has considerable potential. This potential is perhaps greatest on soils of low moisture-holding capacities, or for crops which are at critical growth stages during the periods of the year when rainfall is low. Unlike arid regions, where crop production is impossible without irrigation, growth conditions in humid regions in some years are sufficient to produce high yields. However, in other years, lack of rainfall at critical stages of the season can result in severely reduced yields and reduced quality (Morey and Gilley, 1973).

One of the most important decisions faced by irrigation farmers, particularly those in humid regions, is when to start irrigating. If irrigation is started too soon, water and nutrients may be wasted by leaching, or drainage problems may be created in some soils. Conversely, if irrigation is delayed, the crop may be stressed and yield reduced (Lembke and Jones, 1972). Jensen et al. (1970) concluded that the most important factor affecting irrigation efficiencies and crop yields is scheduling irrigation in time and amount. The importance of irrigation scheduling is magnified when the water supply is short, and costs are high, or when soil conditions exist which restrict water movement, or root development. Procedures for more accurately scheduling irrigations, involving both time and amount, can be separated into those employing direct measurement of soil-moisture levels, and those employing predictive approaches based on estimated soil-moisture depletion.

Harris (1914), in connection with his irrigation work, noted that the time of maturity of corn was delayed by irrigation. He observed that 121 days were required when forty inches of water were applied. Howe and Rhoades (1955), at Scotts Bluff, Nebraska, found that irrigation applied during the tassel to silking period resulted in the highest yield response to water. Additional irrigation applied at the 1-m height, and during the milk stage had a much smaller effect on grain yield.

Stanley and Rhoads (1971) found that corn yields were larger when irrigation was applied at a mean maximum soil-moisture tension at the 15 cm depth of 0.3 bar, rather than at 0.6 cm. Ali (1976) studied the effect of moisture regimes, nitrogen rates, and their interactions on the yield of spring maize germplasm Ganga 7. The treatments consisted of all combinations of 4 moisture regimes (irrigation at 70, 55, 40 and 25 percent available soil moisture) and 4 rates of nitrogen (0, 60, 120, and 180 Kg N/ha). He found that irrigation scheduled at 70 percent available soil moisture (ASM) significantly increased the grain yield when compared with that at 40 percent ASM. Irrigation scheduled at 70, 55 and 40 percent ASM led to significant increases in yield with nitrogen fertilizer up to 180 Kg N/ha.

Schwab et al. (1958) obtained yield increases from irrigation averaging 240 to 605 Kg/ha during a 3-year study in Iowa. The effects of varying the amount of water applied daily by drip irrigation on the yield of corn (*Zea mays* L.) were studied by Lutrick et al. (1975). They found that the yield of Pioneer 3369A was 12,520 Kg/ha (207 bu/acre) without irrigation and reached 14,460 Kg/ha (239 bu/acre) at the 0.75 centimeters of water per day rate. Stone, Gwin, and Dillon (1978) evaluated the influence of irrigation timing on corn (*Zea mays* L.) and sorghum [*Sorghum bicolor* (L.) Moench] yield at Tribune and Manhattan, Kansas in a 3-year study. The 3-year mean yield for corn receiving a single growing-season irrigation was highest when water was applied during early silk emergence. Corn yields responded well to three growing-season irrigations.

Simulation Modeling

The process of developing a model of a real system (prototype) and conducting experiments with this model, in order to measure desired variables, is called simulation. Mathematical simulation techniques are more reasonable to use in a complex system of crop-soil-weather management. Mathematical models and computer-based techniques are methods which will greatly increase the ability to understand, predict, and measure many factors in such complex systems. These methods are usually based on deterministic concepts.

There has been some attention devoted to develop models to predict corn growth under stress. Soil moisture data for many soils in Iowa used in the model developed by Shaw (1963) have resulted in a good estimate of water use by corn. Childs et al. (1976) presented a model simulating the environmental and physiological processes involved in the growth of corn. The model contained two main components, plant growth and water flow. This model has the capability for both predicting plant stress and soil-moisture use. Among the more recent models is that of Barfield et al. (1971) where the response of corn to irrigation was simulated for humid areas. This model is suitable for the prediction of irrigated corn yield despite giving poor results for irrigated yields. Kibler et al. (1977) presented a model to simulate a soil-moisture budget. The main objective of developing this model was to evaluate the consumptive use of applied irrigation water to a crop.

MATERIALS AND METHODS

A major aspect of this research was to calculate the soil moisture under corn throughout the growing season and the yield response to irrigation by using a stress index developed by Shaw (1963, 1974), and by using a soil-moisture simulation model. The original program was modified in order to make it apply more closely to the particular situation being studied.

Computer Program

Original program (program number one)

The soil-moisture program for corn was originally developed by Shaw (1963). The computer program was described by Dale and Hartley (1963), with several minor modifications made at later dates.

The soil-moisture balance is calculated using the amount of water held between the wilting point and field capacity in centimeters for each 15-centimeter layer from the surface to a depth of 150 centimeters, and, in some cases, to a depth of 210 centimeters. Water is added in the soil from precipitation or irrigation, less runoff, and it infiltrates into the soil by filling each 15-centimeter layer to field capacity. Water is lost by evapotranspiration, and excess water above field capacity is percolated out the bottom of the profile.

Evaporation and evapotranspiration losses depend upon the stage of crop development and the weather. The program is usually started in late April or early May, but can be started any time during the growing season. All loss is assumed to be by evaporation at the rate of 0.25 centimeters per day from the first 15-centimeter layer of the soil from the beginning of the program until June 6. From June 7 to September 30, evapotranspiration occurs from the root zone according to the stage of crop development. Denmead and Shaw (1960) estimated the ratio of the daily amount of potential evapotranspiration of corn to open-pan evaporation at various stages of growth (Figure 1). Daily potential evapotranspiration is calculated by multiplying the pan evaporation for each day by the proper factor obtained from the figure. If silking is early, or late, the program is adjusted accordingly.

The relative evapotranspiration rates currently used in the program for different amounts of available soil moisture, and different atmospheric demand conditions, for the period before silking, and the period after silking are shown in Figures 2 and 3.[1] The program determines if soil moisture is adequate to meet the demand for evaporation for that day by using the three curves in Figures 2 or 3. Actual evapotranspiration for each day is calculated by multiplying the potential evapotranspiration by the relative evapotranspiration rate from those figures. A high-demand day is considered as one with pan evaporation greater than 0.75 centimeters. An average-demand day is one with pan-evaporation from 0.5 to 0.75 centimeters, while a low-demand day is one having less than 0.5 centimeters pan evaporation.

Water is extracted from each layer of the soil profile in the pattern shown in Table 1. When an increment of the soil does not have available water, the water that would have been used from that increment is shifted

[1]Personal communication, R. H. Shaw, Iowa State University, 1981.

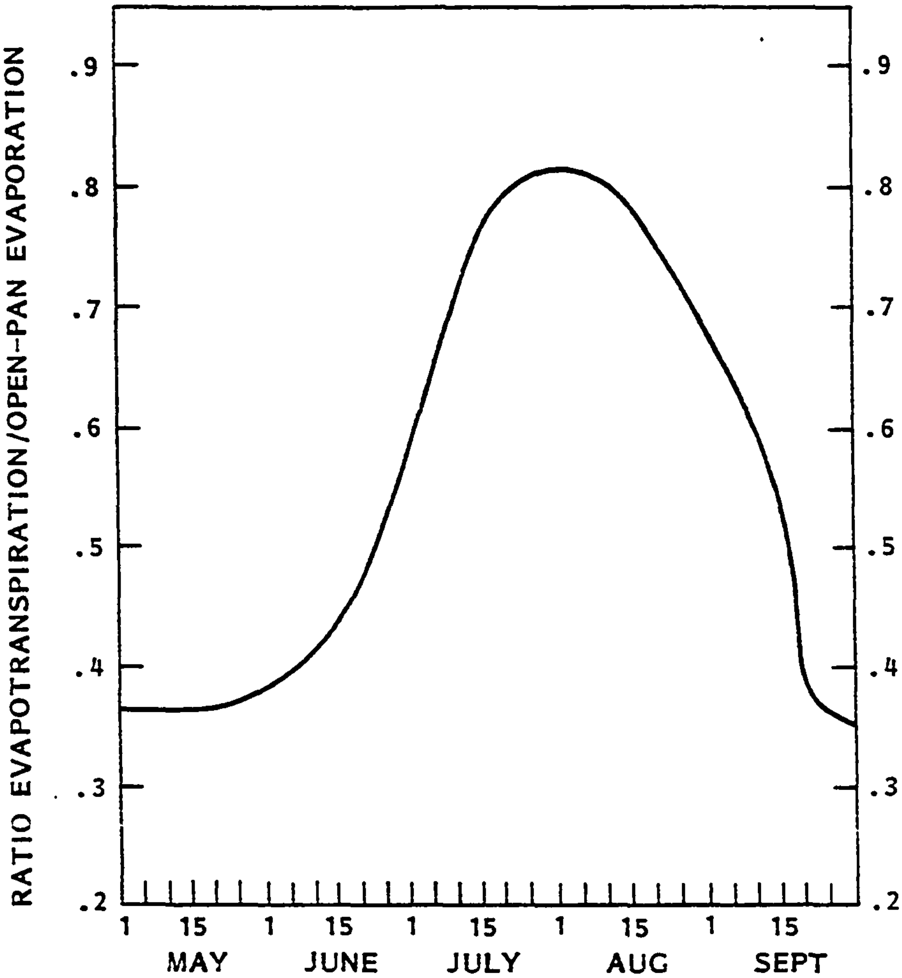


Figure 1. Ratio of potential evapotranspiration of corn to open-pan evaporation throughout the growing season (after Denmead and Shaw, 1960). On the average, 50 percent of the corn in Iowa is silked by July 31

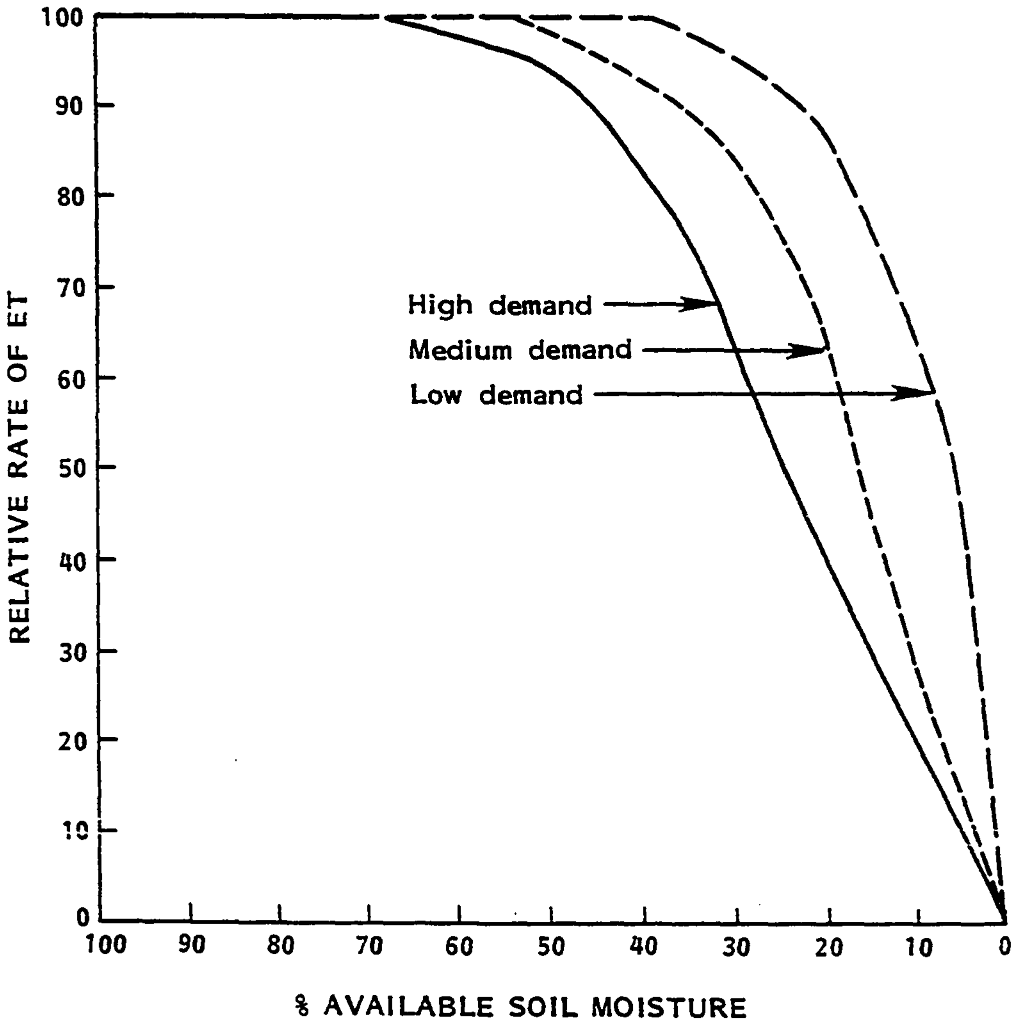


Figure 2. Relative evapotranspiration rate for different atmospheric demand rates prior to August 1 (adjusted for silking date)

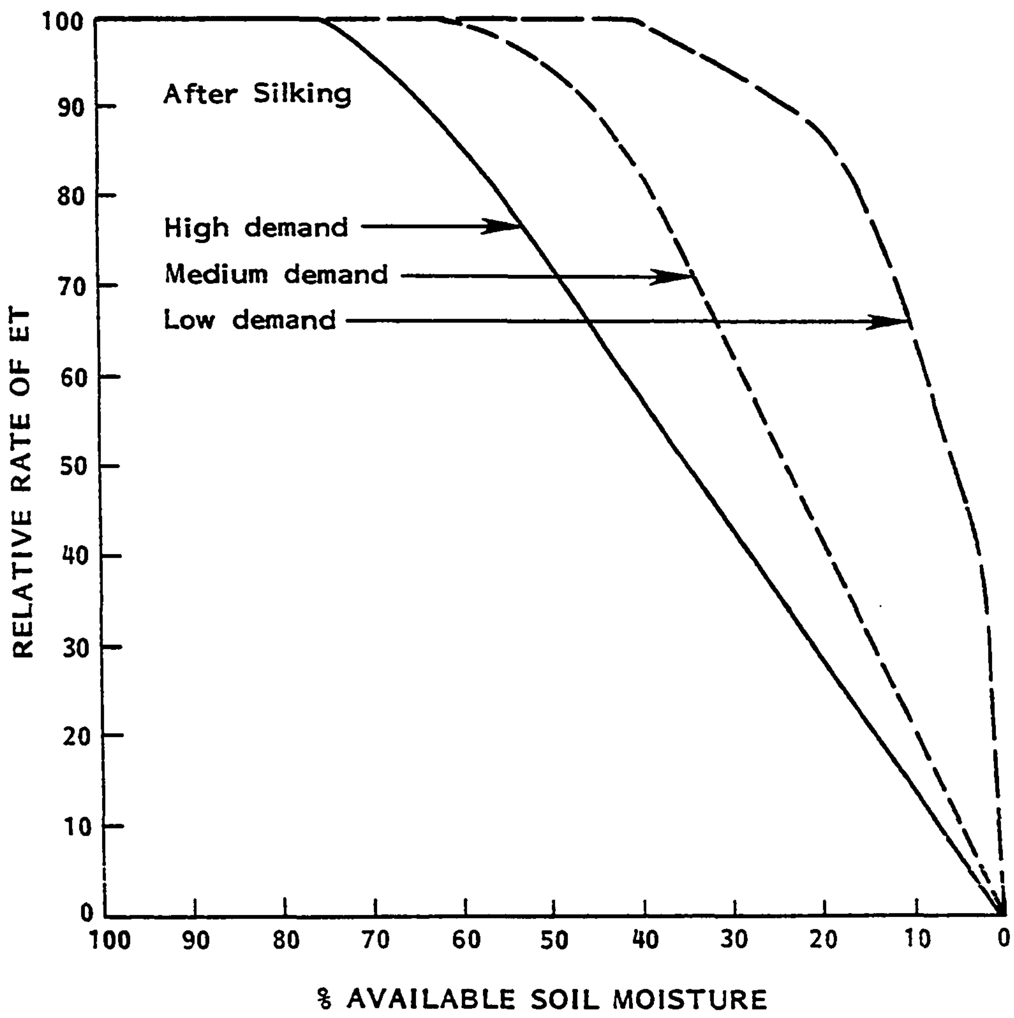


Figure 3. Relative evapotranspiration rate for different atmospheric demand rates after August 1

Table 1. Water extraction from the soil profile at different depths during the growing season; values for each date are given as the percentage of evaporation or evapotranspiration that occurs from each of the depths listed

Date	15-centimeter depths (respective layers numbered from surface								
	1	2	3	4	5	6	7	8	9	10
To June 7	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June 8 to 14	50.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June 15 to 27	33.0	33.0	16.6	16.6	0.0	0.0	0.0	0.0	0.0	0.0
June 28 to July 4	30.0	30.0	10.0	10.0	20.0	0.0	0.0	0.0	0.0	0.0
July 5 to 11	30.0	30.0	10.0	10.0	10.0	10.0	0.0	0.0	0.0	0.0
July 12 to 18	30.0	30.0	7.5	7.5	7.5	7.5	10.0	0.0	0.0	0.0
July 19 to 25	30.0	30.0	7.5	7.5	7.5	7.5	5.0	5.0	0.0	0.0
July 26 to August 1	30.0	30.0	5.0	5.0	5.0	5.0	5.0	5.0	10.0	0.0[a]
	30.0	30.0	7.5	7.5	7.5	7.5	5.0	5.0	0.0	0.0[b]
After August 1	30.0	30.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0[a]
	30.0	30.0	7.5	7.5	7.5	7.5	5.0	5.0	0.0	0.0[b]

[a]Used only if the first 30 centimeters all have < 50 percent available moisture.

[b]Used if only first 120 centimeters have > 50 percent available moisture.

to the other depths where water was being extracted. For days when evapotranspiration is reduced because of moisture stress, additional evaporation can be taking place if recent rains have added water to the soil. Under high-atmospheric-demand conditions (pan evaporation greater than 0.75 centimeters) and stress evapotranspiration greater than or equal to 0.1 cm, zero evaporation is used; otherwise add all evaporation when evaporation is less than 0.13 cm and add 0.13 cm when evaporation is less than or equal to 0.13 cm (see Shaw, 1978, for more details). The flow chart of the program is shown in Figure 4.

Program input At the start of each year, the inputs required in the soil moisture program for computing the daily stress and the water balance for corn are:

1) Date of 75% silking.
2) The amount of water between field capacity and wilting point in centimeters for each 15-centimeter layer. The original program allowed extractions to the 150-centimeter depth. In a later modification for dry conditions in which no percolation occurred through the 150-centimeter profile in May and June, the program allowed the plant to extract water from the 170-centimeter profile rather than just the 150-centimeter profile. To accomplish this, two control cards are needed. The first card includes the 0-150 centimeter depth. On the second card, all of the moisture in the layer from 150 to 170 centimeters is put into the increment between 135 and 150 centimeters. This assumed that the roots had reached the 135-170 centimeter depth

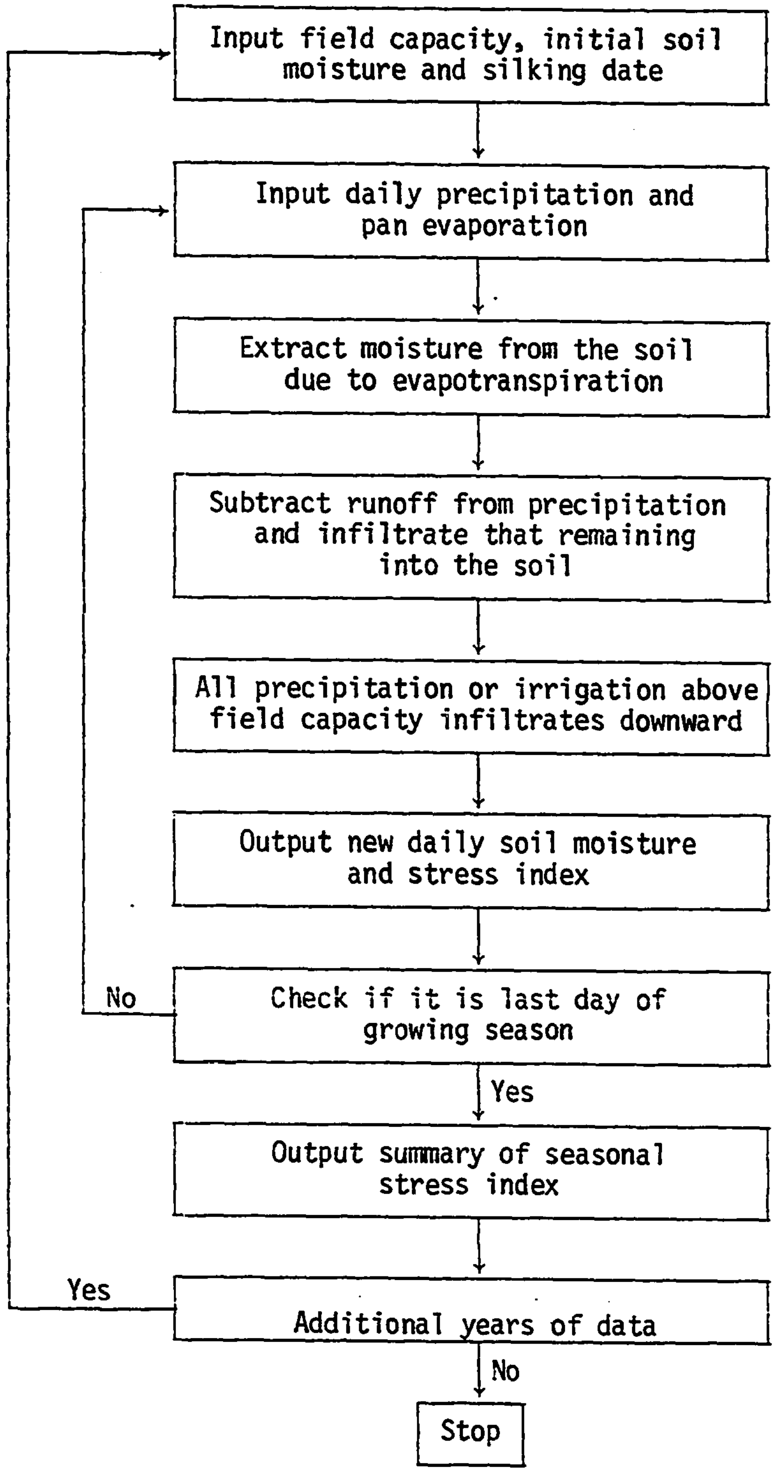


Figure 4. Flow chart of original program

and that all of the moisture from 135-170 centimeters was available to the roots.

3) The amount of plant-available moisture in centimeters is referred to as the initial soil moisture for each 15-centimeter layer. Two control cards were also included for this factor in the same manner as explained under (2).

4) Daily precipitation amount.

5) Daily 24-hour class A pan evaporation.

6) Tables of runoff, ratio of evapotranspiration to open-pan evaporation, relative transpiration rate values, and the moisture extraction schedule are required for the program.

Stress index

The daily stress index (RAWSTR) is computed in two different ways. If stress evapotranspiration (STET) is equal or greater than 0.1 centimeters, and pan evaporation (EVP) is greater than 7.5 centimeters, then

$$RAWSTR = 1 - STET/ET$$

where ET is evapotranspiration when the moisture supply is not limiting. At all other times, the daily stress index is calculated as:

$$RAWSTR = 1 - (STET + EVAP)/ET$$

where EVAP is evaporation from the top 15 centimeters of soil (for more details, see Shaw, 1978).

The stress index is calculated for each day of an 85-day period around the silking date, which included eight 5-day periods before and including the silking date, and nine 5-day periods after the silking date. The weighting factors, which were developed by Shaw in 1974, are given in

Table 2. The stress index, which is calculated for each day, is multiplied by the appropriate weighting factor from Table 2. The daily index is summed for all of the 5-day periods to give the accumulated weighted-stress index.

Table 2. Relative weighting factors used to evaluate the effect of stress on corn yield. Periods are 5-day periods relative to silking (after Shaw, 1974)

Period[a]	Weighting factor	Period	Weighting factor
8 before	0.50	1 after	2.00
7 before	0.50	2 after	1.30
6 before	1.00	3 after	1.30
5 before	1.00	4 after	1.30
4 before	1.00	5 after	1.30
3 before	1.00	6 after	1.30
2 before	1.75	7 after	1.20
1 before	2.00	8 after	1.00
		9 after	0.50

[a]Silking date included in 1 before period.

When 2 or more consecutive 5-day unweighted stress index values were 4.5 or greater, an additional weighting factor of 1.5 was applied. Also, an additional weighting factor of 1.5 was applied to the weighted stress index for those periods of 1 before, 2 before, and 3 before, which had 5-day unweighted stress-index values equal to 3.0, or greater. Crop failure is considered to occur whenever the 5-day unweighted stress-index for periods 1 before and 1 after are both 4.5 or greater. Finally, the sum of all 5-day weighted values gives the seasonal weighted-stress index for the 85-day period. This index has shown to be highly related to the reduction of the corn yield due to stress.

Modified program (program number 2)

The original program was modified in order to approximate the situation in which the soil profile has a claypan layer at some depth in the soil. This program was written for the Cisne Soil, which has a claypan at a depth of 60 centimeters.

In this program, it was assumed that percolation into the claypan layer is zero, no lateral movement occurs, and the soil was impermeable to rooting below the claypan. Daily rainfall, or irrigation water, filled each layer of the soil to field capacity, as was done in original program, then excess moisture above field capacity gradually filled each layer up to saturation, starting from the lowest layer (the layer above the claypan), then filling each layer until the first layer (0-15 centimeters) reached saturation. All moisture above saturation was assumed to runoff from the area.

The extraction pattern was modified to fit the situation with a claypan layer at the depth of 60 centimeters as exists in the Cisne Soil. The modified pattern is given in Table 3. The flow chart for this program is shown in Figure 5.

Additional inputs The saturation values for each 15-centimeter layer of soil are required in addition to the previous inputs. Saturation was assumed to occur when 90% of the pore space was filled with water, except in the first 15-centimeter layer where tillage increases the aeration.

Table 3. Modified water extraction from the soil profile for program number two and three at different depths during the growing season; values for each date are given as the percentage of evaporation and transpiration that occurs from each of the depths listed

Date	15-centimeter depths (respective layers numbered from surface)									
	1	2	3	4	5	6	7	8	9	10
To June 7	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June 8 to 14	50.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June 15 to 27	33.3	33.3	16.6	16.6	0.0	0.0	0.0	0.0	0.0	0.0
After June 27	35.0	35.0	15.0	15.0	0.0	0.0	0.0	0.0	0.0	0.0

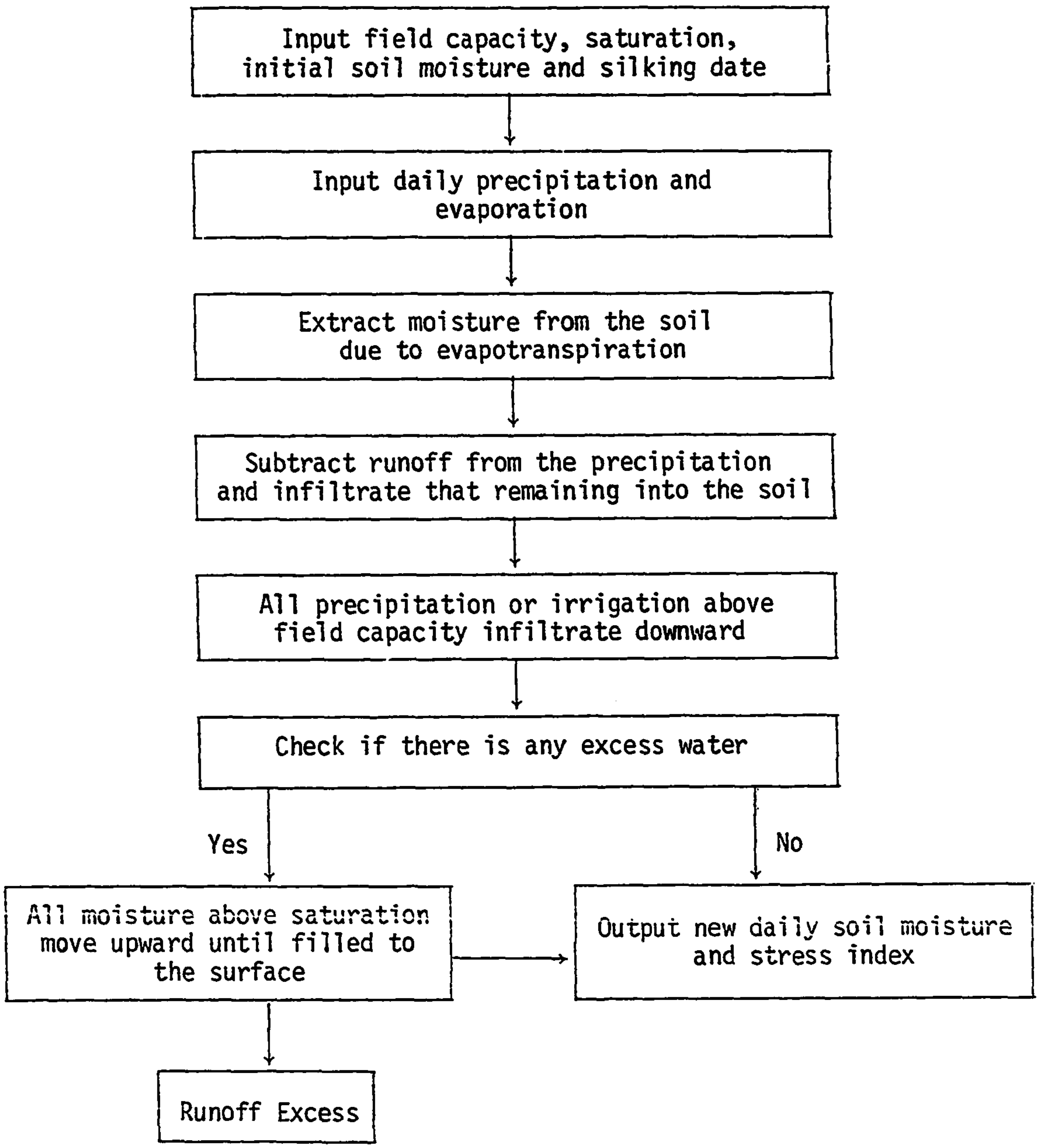


Figure 5. Flow chart of modified program (program number two) showing procedure through calculation of daily soil moisture and stress index

Saturation was assumed when 85% of the pore space in that layer was filled with water. The 85% and 90% values assume some air is trapped in the profile as the saturation process occurs. This assumption was the same as that used by Loveland (1980).

Modified program (program number 3)

The original program was modified by Loveland (1980) for a soil with slow internal drainage. This modified program was used originally for a study of poorly-drained reclaimed strip-mine soils. The infiltration and redistribution of the original program were modified to represent what takes place in a poorly drained soil.

In this program, during infiltration of daily rainfall, each 15-centimeter layer of the root zone is filled to saturation, starting with the top increment. For each day of simulation, a fraction of the amount of moisture contained above field capacity was allowed to percolate downward until each layer reached field capacity, or resaturation happened again due to new rainfall. Thus, the soil profile is allowed to gradually come to field capacity at a rate depending on the soil characteristics. The soil was held at saturation the first day after a rain which saturated the profile, then for the first 30 centimeters of the profile, it was assumed that 25 percent of the soil moisture above field capacity percolated downward. A value of 20 percent was assumed for the rest of the profile. Percolation continues until the soil moisture of each layer reaches field capacity. A flow chart of the subroutine which redistributes the excess moisture downward is given in Figure 6.

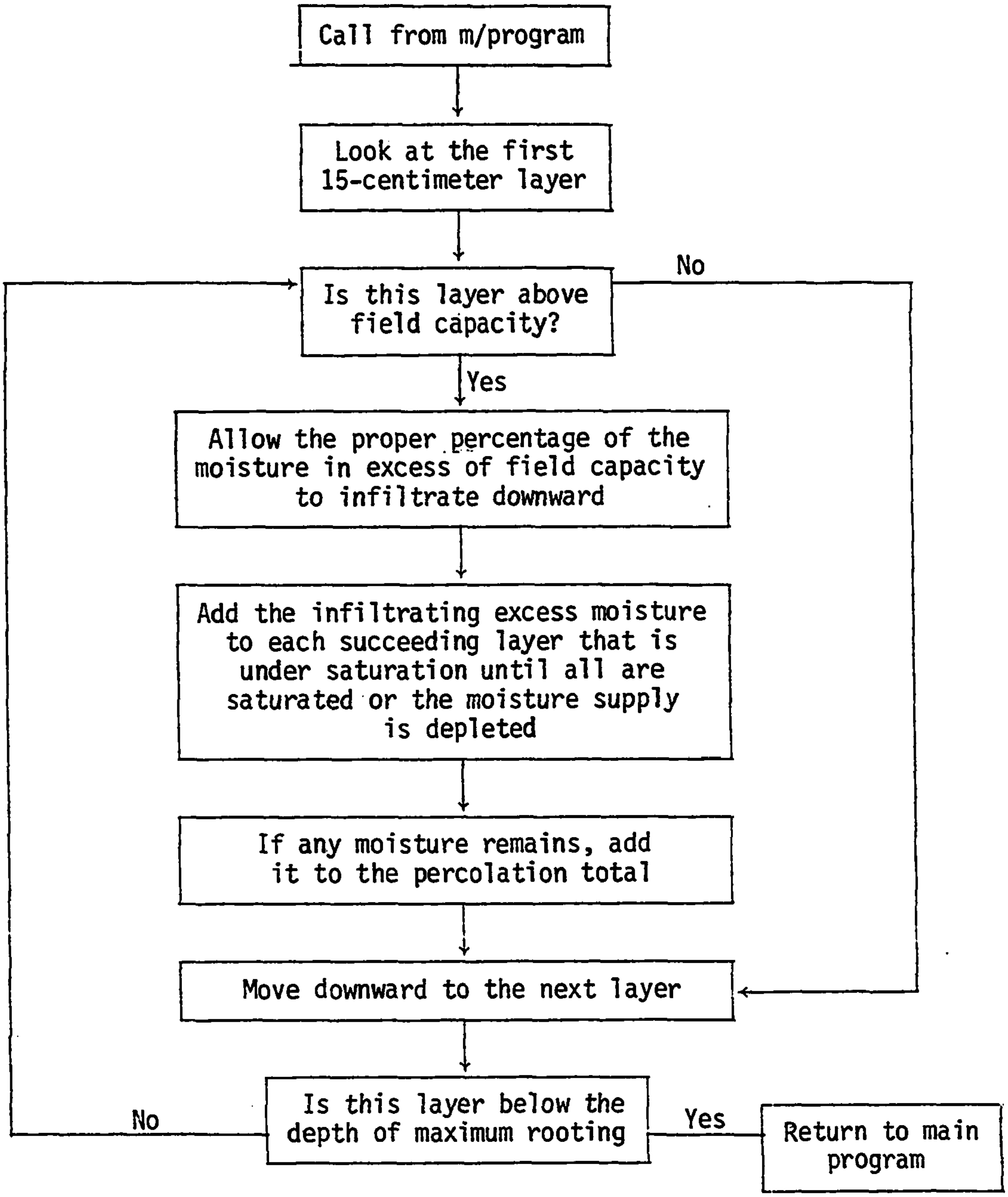


Figure 6. Generalized flow of the redistribution subroutine used in soil moisture program number 3

Excess moisture index

An excess moisture index was developed by Loveland (1980) on the assumption that excess moisture will have detrimental effects on growth. The index equates the number of days between May 3 and July 1 during which the mean air-filled pore space of the top two 15-centimeter layers, expressed as the percent of the total volume is less than, or equal to, 10%. The dates are phenologically adjusted each year according to the silking date. It is during this early part of the growing season that excess moisture has been found to be most harmful to corn. A simple loop was added to both programs number two and three, which computed the excess index.

The index is calculated as:

$$\mathrm{ARTN} = \Big((\mathrm{TPS} - \mathrm{wp}) - (\mathrm{SM} - \mathrm{wp})\Big) / 15 * 100$$

where ARTN is the percentage of the total soil volume containing air at a soil-moisture percent by volume of soil moisture, TPS is the total pore space, wp is the wilting point, and SM is the soil moisture. It is necessary to divide by 15 in order to convert from centimeters to percent by volume. The excess index equals the average of the ARTN values for the top two 15-centimeter layers. More details are given in Loveland (1980).

Irrigation subroutine

A subroutine to simulate irrigation was developed by Nielsen (1979) and added to the soil-moisture program. This subroutine was used to determine the effect of irrigation in reducing the soil-moisture stress on corn.

Irrigation is applied simulating a center-pivot sprinkler irrigation system. Irrigation is scheduled to begin on July 1, or later, whenever the available moisture in the active root zone is less than, or equal to, 75% of the field capacity. At each irrigation, 2.5 centimeters of water is applied every three days, and irrigation continues until the available soil moisture in the active root zone has been brought up to 90% of the field capacity. More details are given in Nielsen (1979).

Moisture stress-yield relationships

Calculations of yearly corn yields (y, Kg/ha) for each run were made using values of 85-day weighted stress index (x) in the equation

$$y = 9682 - 118.6x.$$

This equation gives a no-stress yield of 9682 Kg/ha.

RESULTS AND DISCUSSION

Irrigation of Low Moisture-Capacity Soils in Iowa

Eight sites were chosen to evaluate the effect of irrigation on corn yields on low moisture-capacity soils in Iowa. Weather data from regular Iowa soil-moisture sites were used in this study, even though the low capacity soils were not present on the experimental site. A brief description of each site location is given in Table 4. The descriptions of these sites were taken from Zanzalari (1973). The relative locations of the sites are shown in Figure 7. The plant-available-moisture capacity values for the soils used in this study are given in Table 5. The moisture characteristics for the low-water-holding capacity soils were provided by the Soil Survey Unit, Iowa State University (private communication, Thomas Fenton, 1980), and are typical for low moisture-capacity soils in each area.

Distribution of Irrigated Corn Yields and Yield Increase Due to Irrigation

The original soil - moisture program was used for the stations in Iowa. The unirrigated and the irrigated yield and the yield increase due to irrigation for the stations are summarized in Tables 6, 7, 8, 9, 10, 11, 12 and 13. It can be seen from the tables that some reduction of yield due to moisture stress is present in nearly every year at all stations, but for most locations, this reduction is not severe. In all parts of the state, greater overall productivity would be possible if sandy soils were irrigated. Table 14 summarizes the average yield increases for all stations. Figures 8, 9, and 10 show the frequency distributions of the yield increase due to irrigation for Doon, Ames, and Cedar Rapids, respectively.

Table 4. Location of the Iowa soil-moisture sampling sites and soil type used in the study for each location

Stations	Area of state	Soil-moisture sampling site	Soil type used in study
Doon	Northwest	Northwest research center	Bolan
Castana	Western	Western Iowa research center	Waukee
Norwich-Shenandoah	Southwest	Until 1966, soil conservation center - then Earl May Trial Gardens	Grable
Kanawha	North central	Northern Iowa research center	Wadena
Ames	Central	Iowa State University Agronomy and Agricultural Engineering Research Center	Wadena
Elkader	Northwest	Six miles southeast of town	Saude
Cedar Rapids	East central	Four miles southeast of town	Waukee
Burlington-Columbus Junction	Southeast	Until 1968, at Burlington Ordnance Plant, then changed to five miles south of Columbus Junction	Waukee

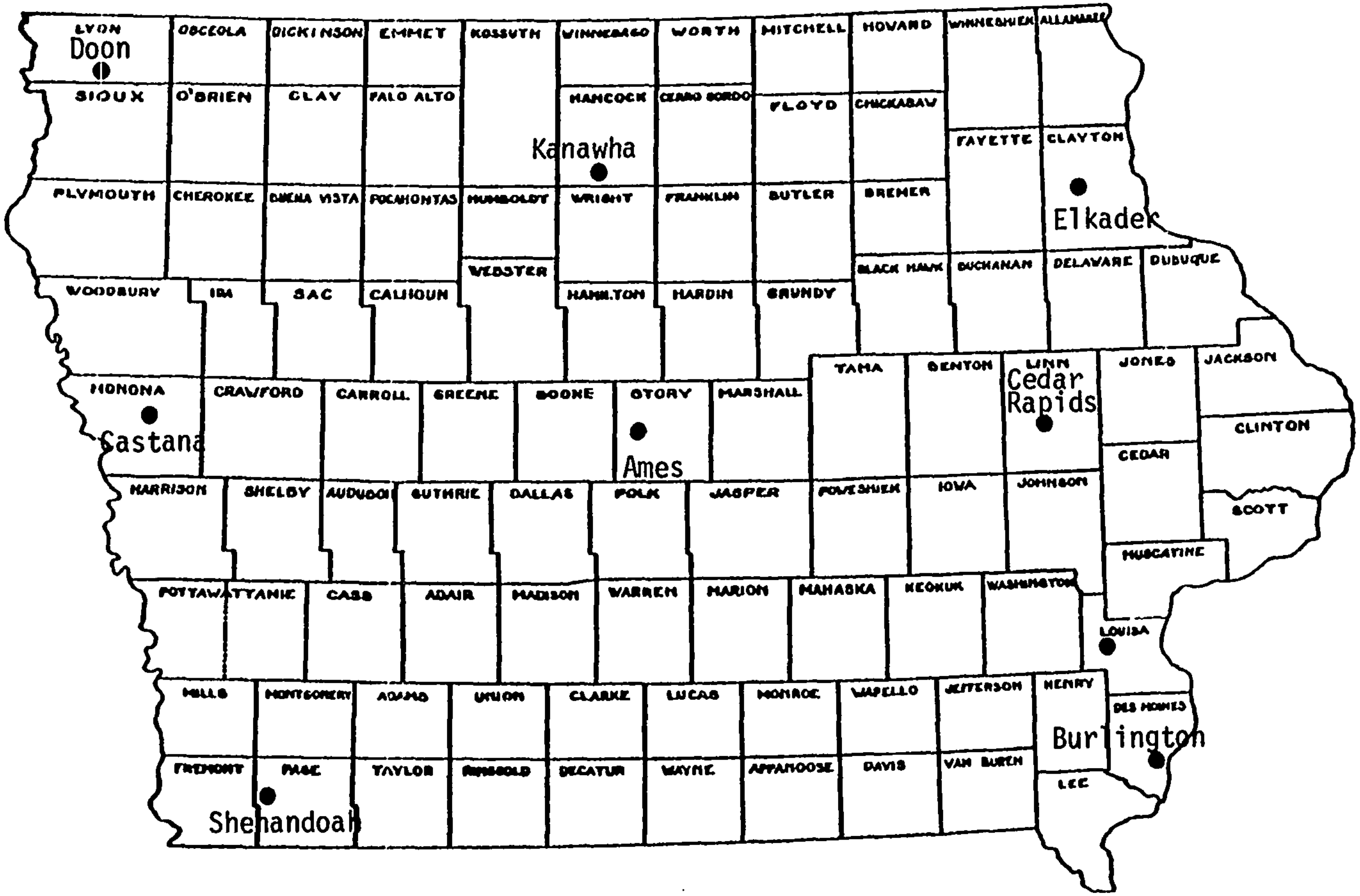


Figure 7. Location of soil-moisture sites

Table 5. Plant-available-moisture capacity in centimeters of sandy soils in Iowa

Stations	Typical soil used in study	Depth in centimeters									
		0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
Doon	Bolan	3.00	3.00	3.00	2.90	2.40	2.40	1.87	1.35	1.35	1.35
Castana	Waukee	2.70	2.70	2.55	2.25	2.25	1.98	0.60	0.60	0.60	0.60
Norwich-Shenandoah	Grable	3.40	3.40	3.04	3.40	0.75	0.75	0.75	0.75	0.75	0.75
Kanawha	Wadena	2.70	2.70	2.55	2.25	2.25	1.98	0.60	0.60	0.60	0.60
Ames	Wadena	2.70	2.70	2.55	2.25	2.25	1.98	0.60	0.60	0.60	0.60
Elkader	Saude	3.15	3.15	2.65	2.55	1.90	0.60	0.60	0.60	0.60	0.60
Cedar Rapids	Waukee	2.70	2.70	2.55	2.25	2.25	1.98	0.60	0.60	0.60	0.60
Burlington-Columbus Junction	Waukee	2.70	2.70	2.55	2.25	2.25	1.98	0.60	0.60	0.60	0.60

Table 6. Unirrigated and irrigated corn yield and yield increase due to irrigation at Doon, Iowa for sandy soil (Bolan)

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1958	4947	9674	4727
59	4171	9682	5511
60	9293	9682	389
61	8328	9682	1354
62	9445	9682	237
63	3036	9682	6646
64	9131	9682	551
65	8769	9682	913
66	6175	9682	3507
67	4153	9682	5529
68	2641	9682	7041
69	9610	9682	72
70	507	9682	9175
71	6560	9682	3122
72	9682	9682	0
73	9012	9682	670
74	4733	9682	4949
75	7000	9682	2682
76	2502	9121	6619
77	8162	9682	1520
Average	6393	9654	3261

Table 7. Unirrigated and irrigated corn yield and yield increase due to irrigation at Castana, Iowa for sandy soil (Waukee)

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1958	9552	9682	130
59	5956	9651	3695
60	9280	9682	402
61	7756	9682	1926
62	9094	9682	588
63	9402	9682	280
64	8587	9682	1095
65	8248	9682	1434
66	8644	9682	1038
67	5880	9682	3802
68	7359	9682	2323
69	9553	9682	129
70	5622	9682	4060
71	5746	9682	3936
72	9665	9682	17
73	9012	9682	670
74	5409	9682	4273
75	5932	9682	3750
76	0	9333	9333
77	8246	9682	1436
Average	7447	9663	2216

Table 8. Unirrigated and irrigated corn yield and yield increase due to irrigation at Norwich-Shenandoah, Iowa for sandy soil (Grable)

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1958	9682	9682	0
59	9611	9682	71
60	9125	9682	557
61	9682	9682	0
62	8436	9682	1246
63	8496	9682	1186
64	7443	9682	2239
65	9219	9682	463
66	8908	9682	774
67	7032	9682	2650
68	5259	9469	4210
69	9490	9682	192
70	4385	9607	5222
71	5680	9640	3960
72	9072	9682	610
73	8464	9682	1218
74	4078	9682	5604
75	5882	9682	3800
76	4856	9682	4826
77	5658	9598	3940
Average	7523	9661	2138

Table 9. Unirrigated and irrigated corn yield and yield increase due to irrigation at Kanawha, Iowa for sandy soil (Wadena)

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1958	8482	9682	1200
59	6687	9622	2935
60	5786	9682	3896
61	8738	9682	944
62	9682	9682	0
63	9517	9682	165
64	9080	9682	602
65	9195	9682	485
66	7763	9682	1919
67	7053	9682	2629
68	9657	9682	25
69	9511	9682	171
70	6142	9682	3540
71	8638	9682	1044
72	9658	9682	24
73	7629	9682	2053
74	6874	9682	2808
75	6921	9682	2761
76	1382	9682	8300
77	6354	9530	3176
Average	7737	9671	1934

Table 10. Unirrigated and irrigated corn yield and yield increase due to irrigation at Ames, Iowa for sandy soil (Wadena)

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1958	9669	9682	13
59	7746	9623	1877
60	9345	9682	337
61	9549	9682	133
62	8616	9682	1066
63	9422	9633	211
64	8802	9682	880
65	7067	9682	2615
66	5662	9682	4020
67	7000	9682	2682
68	8592	9682	1090
69	9323	9682	359
70	7521	9682	2161
71	6602	9668	3066
72	9681	9682	1
73	9008	9682	674
74	6912	9682	2770
75	6723	9682	2959
76	2832	9682	6850
77	3639	7973	4334
Average	7685	9590	1905

Table 11. Unirrigated and irrigated corn yield and yield increase due to irrigation at Elkader, Iowa for sandy soil (Saude)

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1958	9682	9682	0
59	9402	9682	280
60	9682	9682	0
61	9682	9682	0
62	9682	9682	0
63	6111	9682	3571
64	5472	9682	4210
65	8640	9682	1042
66	7867	9682	1815
67	8354	9682	1328
68	9682	9682	0
69	8224	9682	1458
70	8814	9682	868
71	8688	9682	994
72	9682	9682	0
73	7465	9682	2217
74	9582	9682	100
75	7196	9682	2486
76	2609	9682	7073
77	7694	9262	1568
Average	8210	9661	1451

Table 12. Unirrigated and irrigated corn yield and yield increase due to irrigation at Cedar Rapids, Iowa for sandy soil (Waukee)

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1958	9682	9682	0
59	9673	9682	9
60	8287	9682	1395
61	9682	9682	0
62	9512	9682	170
63	9261	9493	232
64	7674	9682	2008
65	9682	9682	0
66	7242	9682	2440
67	9302	9682	380
68	9381	9682	301
69	9671	9682	11
70	9682	9682	0
71	8586	9682	1096
72	9682	9682	0
73	8638	9682	1044
74	9682	9682	0
75	6010	9682	3672
76	7066	9682	2616
77	8447	9512	1065
Average	8842	9664	822

Table 13. Unirrigated and irrigated corn yield and yield increase due to irrigation at Burlington-Columbus Junction, Iowa for sandy soil (Waukee)

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1958	9682	9682	0
59	8457	9681	1224
60	7630	9682	2052
61	9682	9682	0
62	7605	9682	2077
63	8179	9464	1285
64	6929	9682	2753
65	8029	9682	1653
66	4840	9682	4842
67	9158	9682	524
68	9668	9682	14
69	9572	9682	110
70	9682	9682	0
71	7738	9682	1944
72	9682	9682	0
73	9682	9682	0
74	9645	9682	37
75	6603	9682	3079
76	7510	9682	2172
77	9038	9630	592
Average	8450	9668	1218

Table 14. Average yield of unirrigated and irrigated corn and increase due to irrigation

Station	Ave. yield unirrigated Kg/ha	Ave. yield irrigated Kg/ha	Ave. increase Due to irrigation Kg/ha	% yield increase due to irrigation
Doon	6393	9654	3261	51
Castana	7447	9663	2216	30
Norwich-Shenandoah	7523	9661	2138	28
Kanawha	7737	9671	1934	25
Ames	7685	9590	1905	25
Elkader	8210	9661	1451	18
Cedar Rapids	8842	9664	822	9
Burlington-Columbus Junction	8450	9668	1218	14

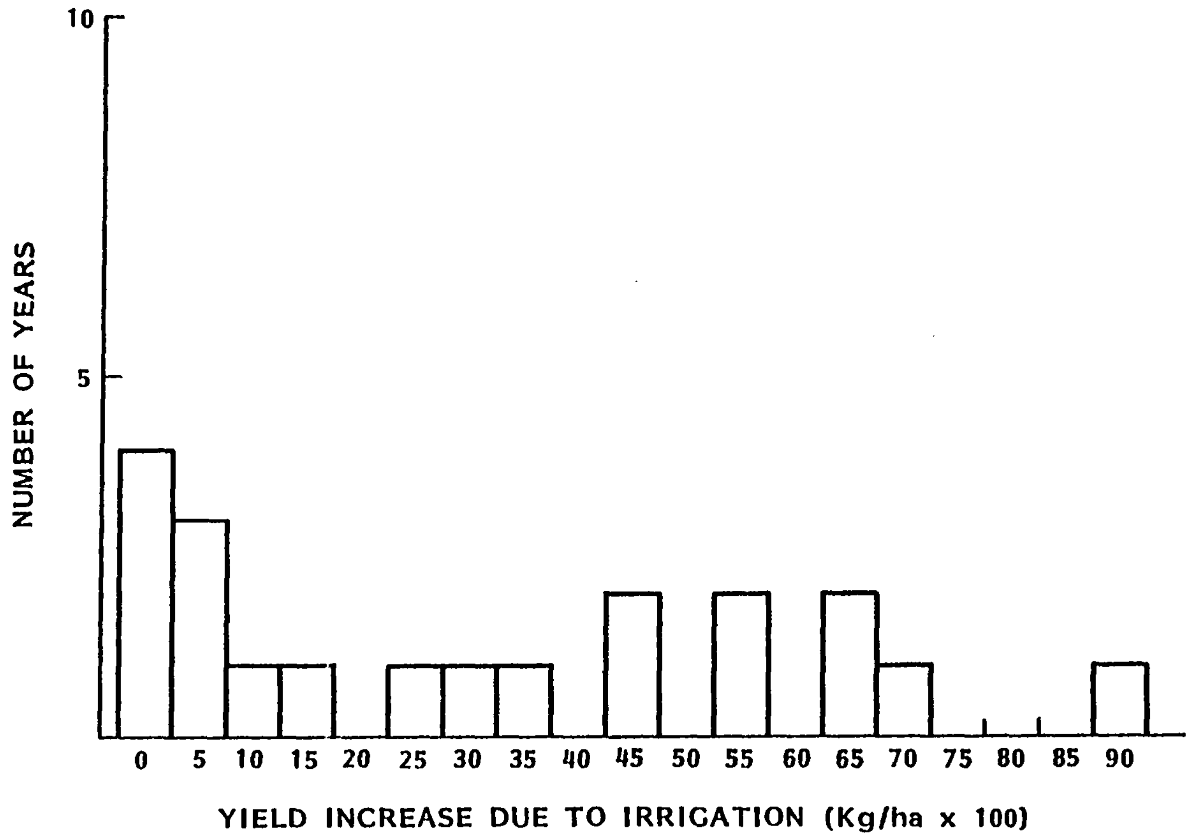


Figure 8. Distribution of yield increases due to irrigation at Doon, Iowa, 1958-1977

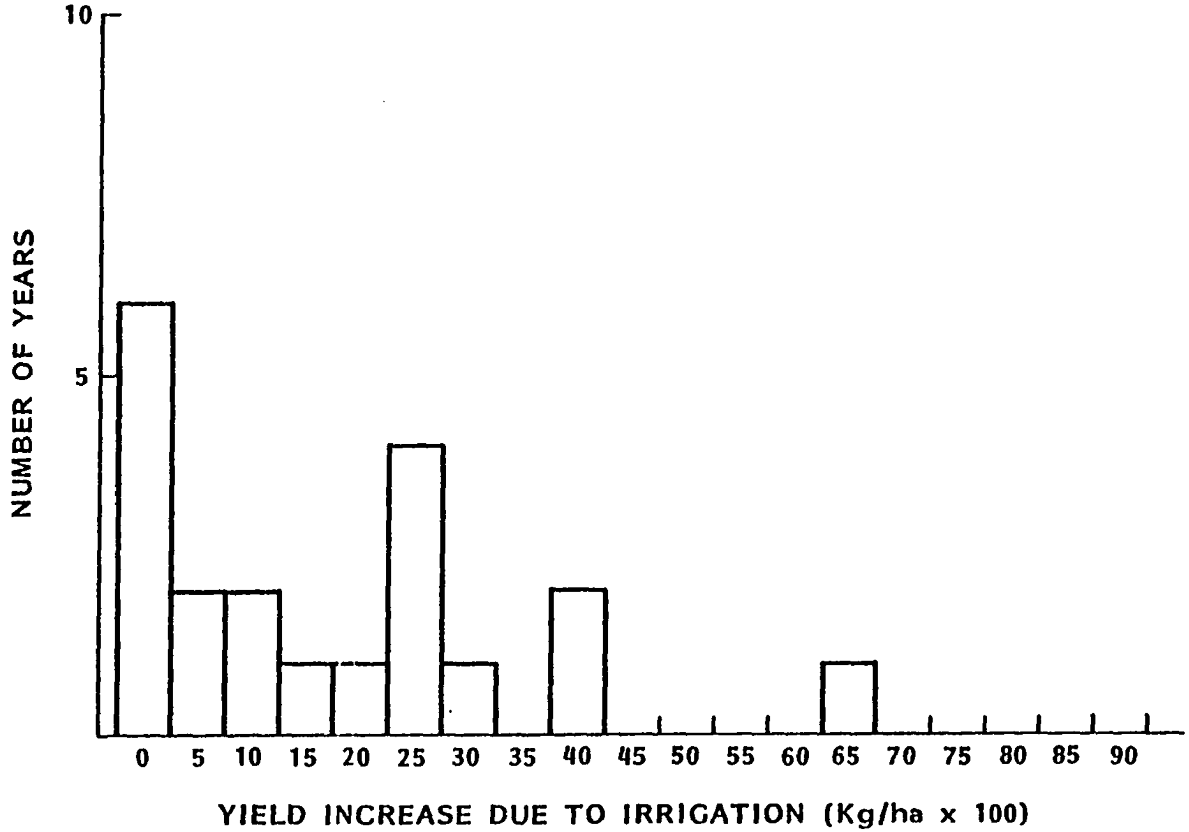


Figure 9. Distribution of yield increases due to irrigation at Ames, Iowa, 1958-1977

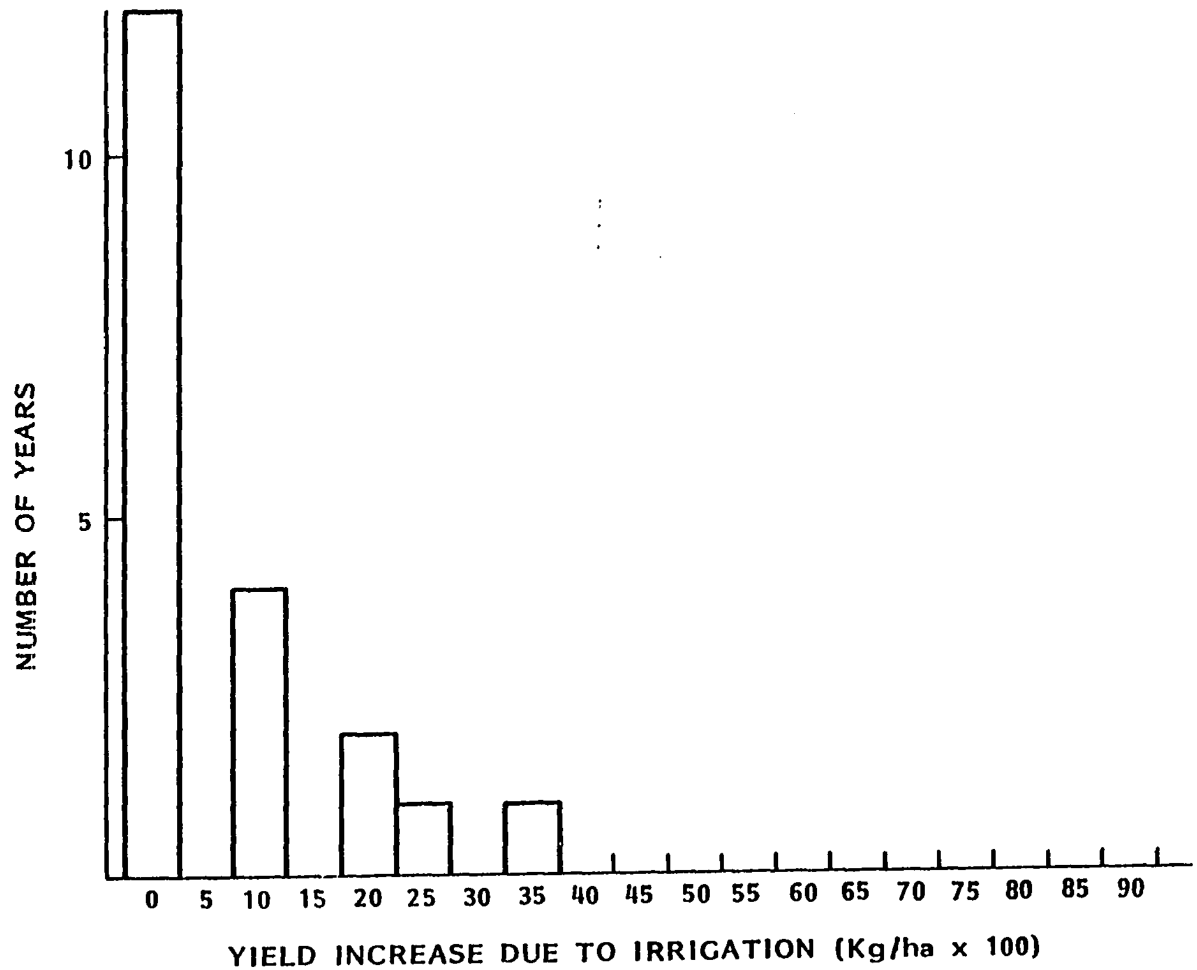


Figure 10. Distribution of yield increases due to irrigation at Cedar Rapids, Iowa, 1958-1977

In northwest Iowa (Doon), a yield increase occurred in 18 out of 20 years (Table 6). The average yield computed for natural rainfall conditions was 6393 Kg/ha and the average yield, with irrigation, was 9654 Kg/ha (Table 14). With irrigation, the yield increase ranged from 0 to 9175 Kg/ha for the 20 years (Figure 8) and was over 3000 Kg/ha in 10 of the 20 years. The average yield increase was 3261 Kg/ha or 51 percent at this station (Table 14). In southwest Iowa, the increase in yield was not as great as in northwest Iowa. The average yield increase was 2138 Kg/ha at Norwich-Shenandoah (Table 14) and the increases ranged from 0 to 5604 Kg/ha (Table 8). Castana, in west-central Iowa, had an average yield increase of 2216 Kg/ha (Table 14) and ranged from 17 to 9333 Kg/ha (Table 7).

In central Iowa (Ames), the average yield under natural weather conditions was 7685 Kg/ha (Table 14). The average yield increase was 1934 Kg/ha with an average yield increase of about 25 percent due to irrigation (Table 14). With irrigation, the yield increases ranged from 1 to 6850 Kg/ha, and were less than 2000 Kg/ha in 11 of the 20 years (Figure 9). In north-central Iowa, Kanawha, the average yield increase was 1934 Kg/ha (Table 14). With irrigation, yield increases ranged from 0 to 8300 Kg/ha (Table 9).

In eastern Iowa, yield increases were much smaller, averaging 822 Kg/ha at Cedar Rapids, 1218 Kg/ha at Burlington, and 1451 Kg/ha at Elkader (Table 14). The yield increases for these stations fell in the range of 0 to 3672 Kg/ha at Cedar rapids, 0 to 4842 Kg/ha at Burlington and 0 to 7073 Kg/ha at Elkader (Tables 11, 12, 13). At Cedar Rapids, in 16 out of 20 years, yield increases were less than 2000 Kg/ha (Figure 10).

The overall results from these data show that the maximum yield increases due to irrigation are less in eastern than central and northwest

Iowa. Figure 11 shows the isolines of average yield increase due to irrigation in Iowa. The average yield increases ranged from 822 Kg/ha at Cedar Rapids to 3261 Kg/ha at Doon. This shows that moisture stress occurs to a lower degree in eastern Iowa. Most of this reduction in yield could be removed by irrigation, which would also reduce the year-to-year variation in yield. Crop productivity would tend to be uniform for all stations, and much higher productivity would be possible. The results show that on low-moisture holding capacity soils in a climatic region where rainfall often is deficient, the yield response to irrigation is significant because the low soil-moisture supply can be depleted rapidly if dry weather occurs. On higher holding capacity soils, the reserve is often much greater and the irrigation response much smaller. Nielsen (1979) found increases in corn yield due to irrigation on high water-holding capacity soils were greater in northwest Iowa (2197 Kg/ha) and least in east and southwest Iowa (628 Kg/ha).

Amount of Irrigation Water Applied

The average seasonal applications of irrigation water, and the range in centimeters of water applied, are given in Table 5. The distribution of irrigation water for Doon and Cedar-Rapids are shown in Figures 12 and 13.

In northwest Iowa (Doon), an average of 22 centimeters/year of water was applied and the range was 10 to 47.5 centimeters/year (Figure 12). In western Iowa (Castana and Shenandoah), an average of 18.5 centimeters and 19.5 centimeters/year of water was applied with the range from 10 to 45 centimeters/year at Castana and 7.5 to 32.5 centimeters/year at Shenandoah (Table 15).

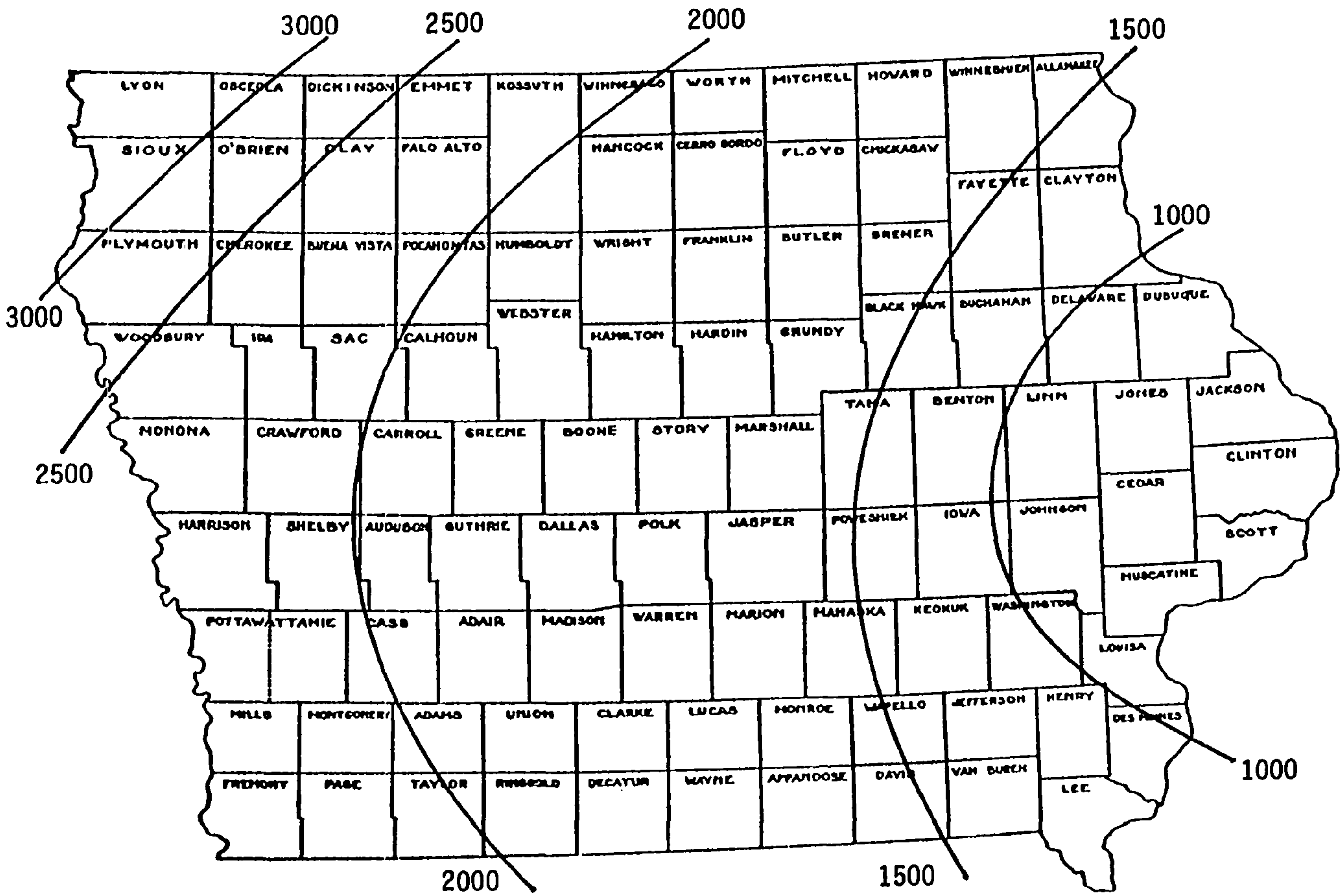


Figure 11. Average yield increase in Kg/ha due to irrigation in Iowa of low moisture capacity soil

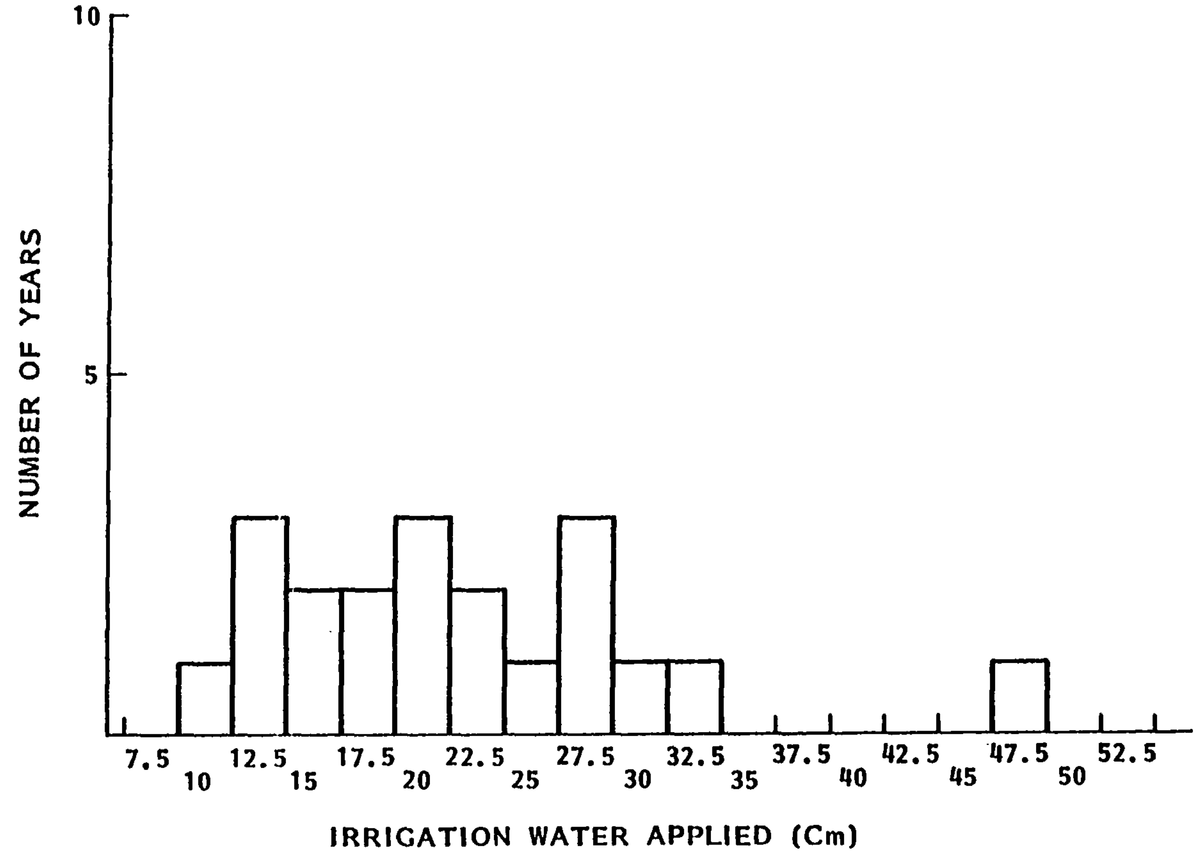


Figure 12. Distributions of seasonal irrigation application at Doon, Iowa, 1958-1977

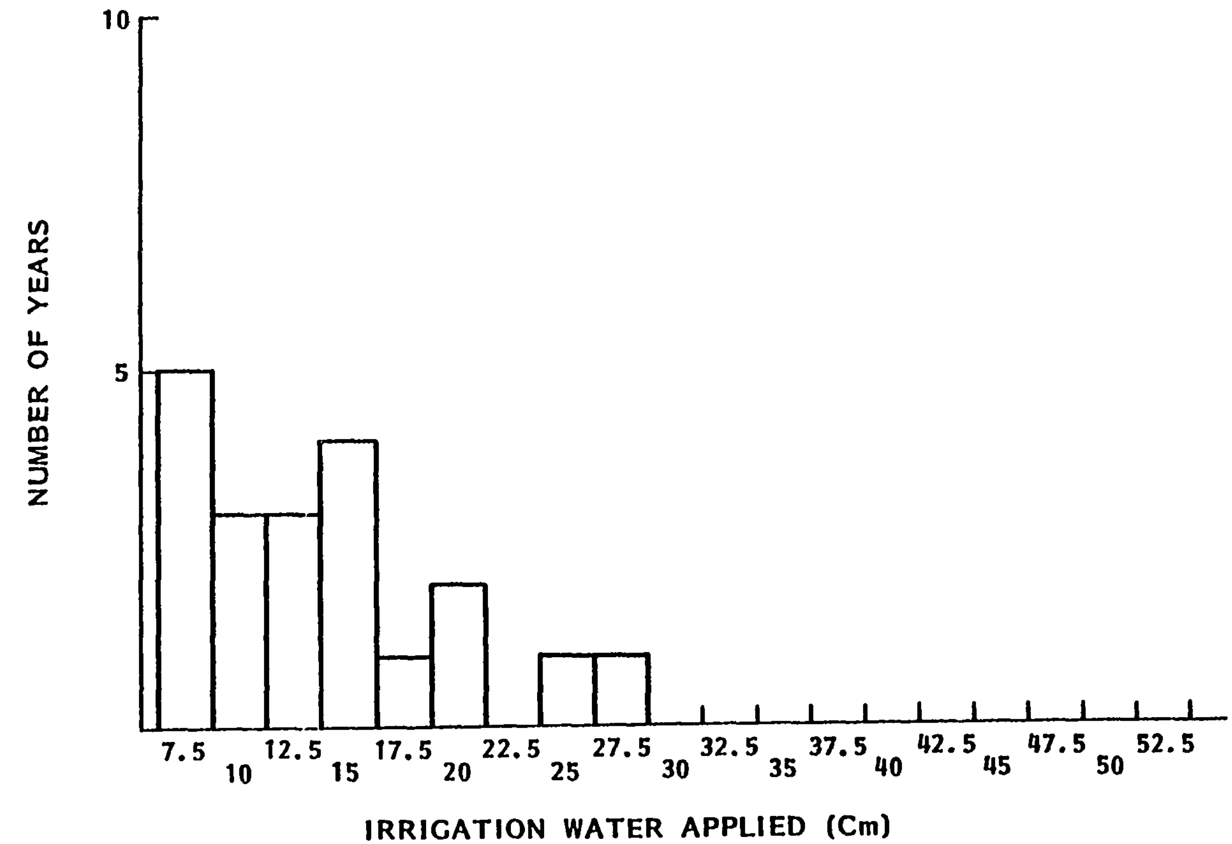


Figure 13. Distributions of seasonal irrigation application at Cedar Rapids, Iowa, 1958-1977.

Table 15. Average total application of irrigation water from July 1 to September 30 and the range in centimeters of water applied

Station	Water applied (cm)	Range of water applied (cm)
Doon	22	10-47.5
Castana	18.5	10-45
Norwich-Shenandoah	19.5	7.5-32.5
Kanawha	18	7.5-40
Ames	18.5	7.5-37.5
Elkader	15.5	0-37.5
Cedar Rapids	14	7.5-27.5
Burlington-Columbus Junction	15.5	5-27.5

In north-central and central Iowa, an average of 18.5 centimeters/year water was applied at Ames and 18 centimeters/year at Kanawha. The range was 7.5 to 37.5 centimeters/year at Ames and 7.5 to 40 centimeters/year at Kanawha, similar to the values in western Iowa (Table 15).

In eastern Iowa (Elkader, Cedar Rapids and Burlington), 15.5 centimeters/year, 14 centimeters/year and 15.5 centimeters/year of water was applied; the range was 0 to 37.5, 7.5 to 27.5 and 5 to 27.5 centimeters/year, respectively (Table 15).

The greatest ranges of water applied were at Doon, Castana, Kanawha and Elkader. Figure 14 shows the isolines of the average irrigation water applied in Iowa. The greatest amounts were applied in northwest Iowa (Doon), and the least amounts were applied in eastern Iowa. The mean annual

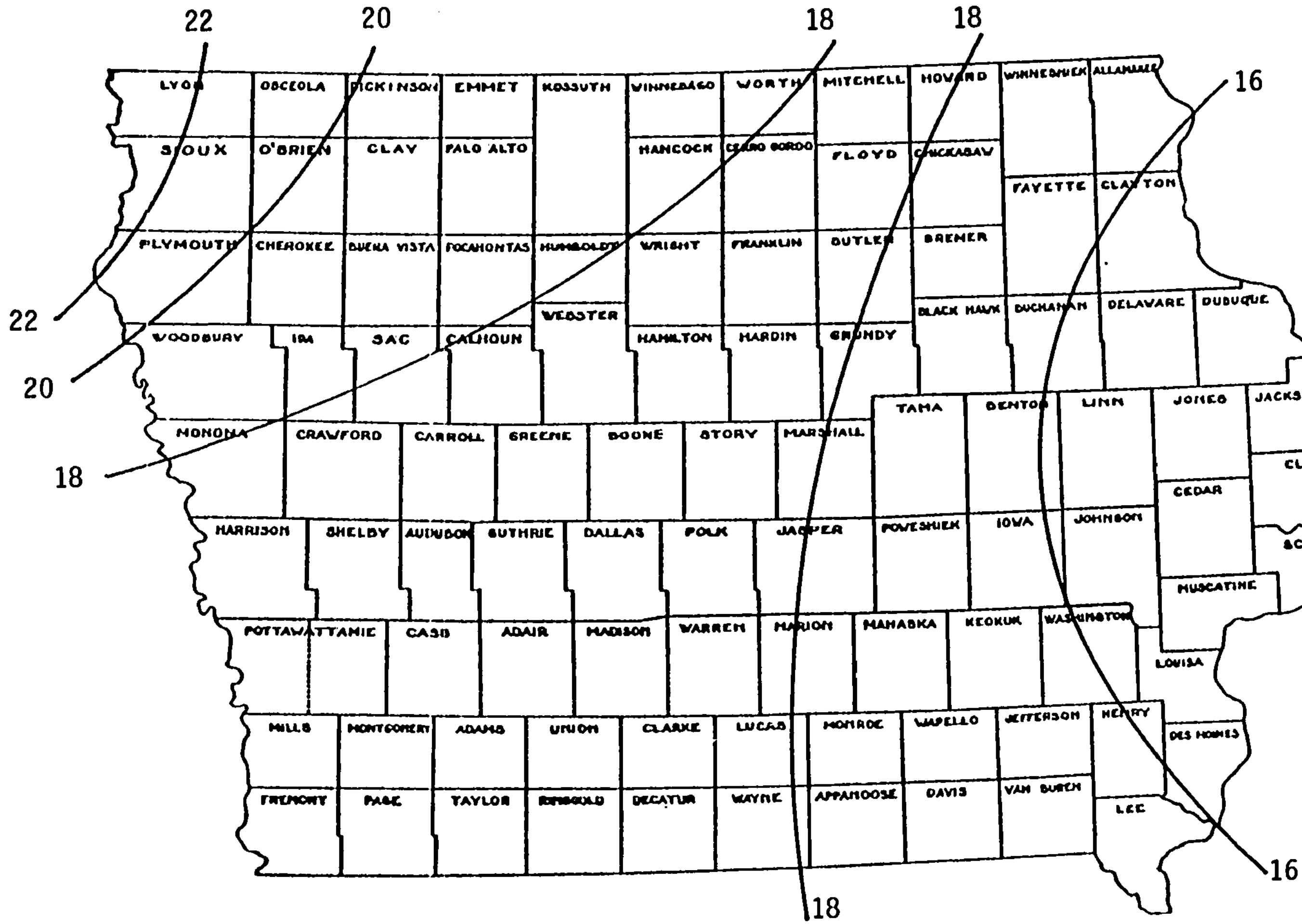


Figure 14. Average irrigation water applied in Iowa (cm) on low moisture capacity soils

precipitation is lower in northwest Iowa and evaporation is higher. With a lower soil-moisture supply, lower summer rainfall and higher evaporation, more irrigation water will be required.

Distribution of Total Percolation in July, August and September

The average total percolation amounts in July, August and September, and the range of percolation values are summarized in Table 16. Percolation was low for the unirrigated condition. In Northwest Iowa (Doon), the average percolation was 2.5 centimeters, and the range was 0 to 12.5 centimeters with irrigation. In western Iowa (Castana and Shenandoah), the average percolation with irrigation was 4.1 centimeters and 5.7 centimeters and the range was 0-15 and 0-16 centimeters, respectively. In north-central and central Iowa (Ames and Kanawha), percolation ranged from 0 to 16.7 and 0 to 28 centimeters and the average with irrigation was 5.8 centimeters and 5.1 centimeters, respectively. In eastern Iowa (Elkader, Cedar Rapids and Burlington), the percolation range was 0.85 to 18.3, 0 to 23 and 0 to 21.6 centimeters and the average was 6.2, 7.2 and 8.1 centimeters, respectively. The frequency distribution of total percolation for the unirrigated and irrigated plots for Doon, which has the lowest, and Cedar Rapids, which has the highest, are given in Figures 15 and 16. High amounts of percolation may result in leaching of nutrients and chemicals. Results show that the frequency of possible leaching is low in northwest Iowa and high in eastern Iowa in low-moisture-holding capacity soils when irrigation is applied.

Table 16. Average total percolation water in July, August, and September and the range of percolation (cm)

Station	Ave. percolation water (cm)		Range of percolation water (cm)	
	Unirrigated	Irrigated	Unirrigated	Irrigated
Doon	0.1	2.5	0-2.1	0-12.5
Castana	0.2	4.1	0-3.1	0-15.0
Norwich-Shenandoah	1.3	5.7	0-7.2	0-16.0
Kanawha	1.5	5.1	0-17.2	0-28.1
Ames	1.0	5.8	0-5.7	0-16.7
Elkader	1.2	6.2	0-11.5	0.8-18.3
Cedar Rapids	2.9	7.2	0-18.7	0-23.0
Burlington-Columbus Junction	3.0	8.1	0-11.3	0-21.0

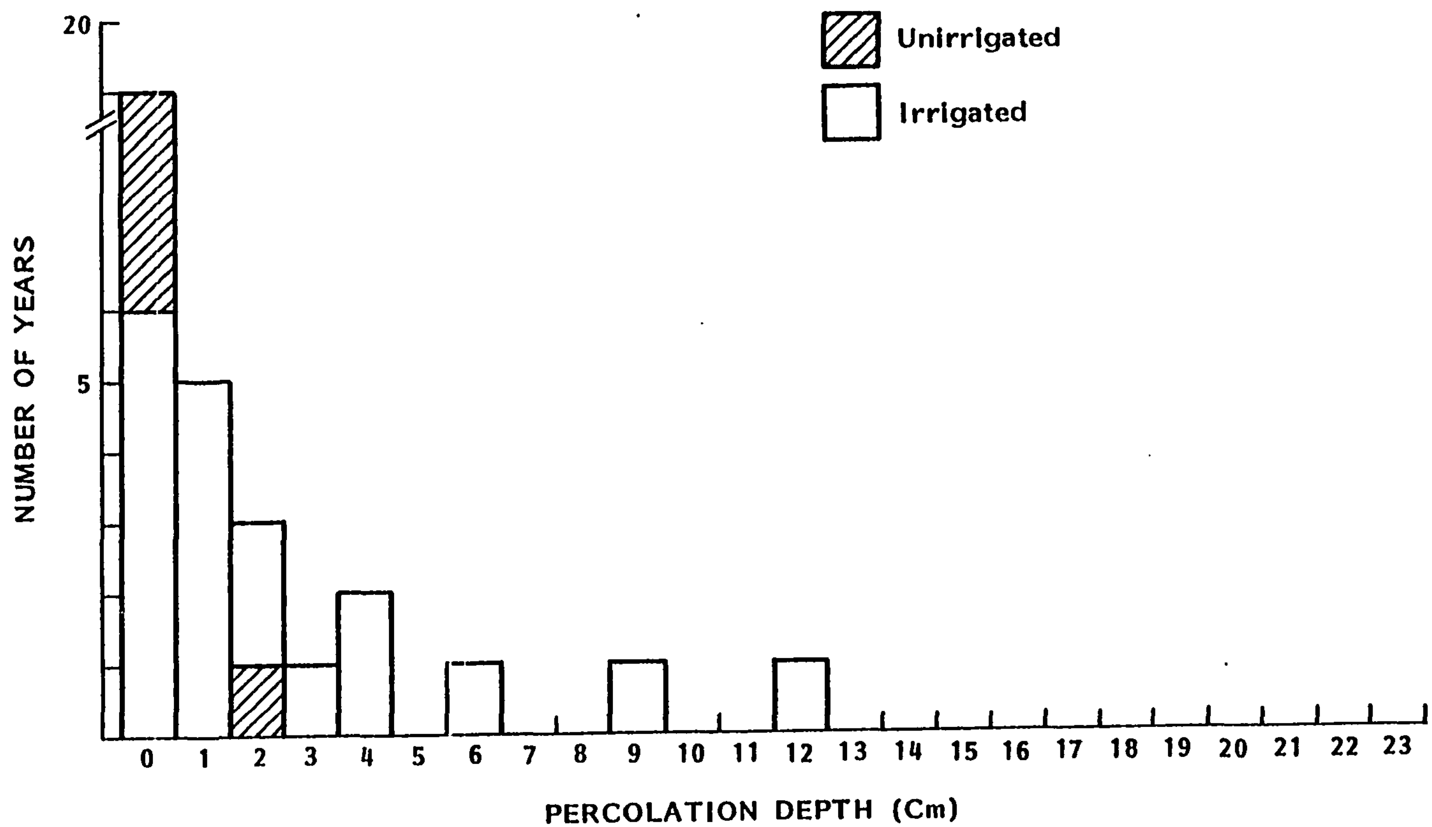


Figure 15. Distributions of total percolation in July, August, and September at Doon, Iowa, 1958-1977

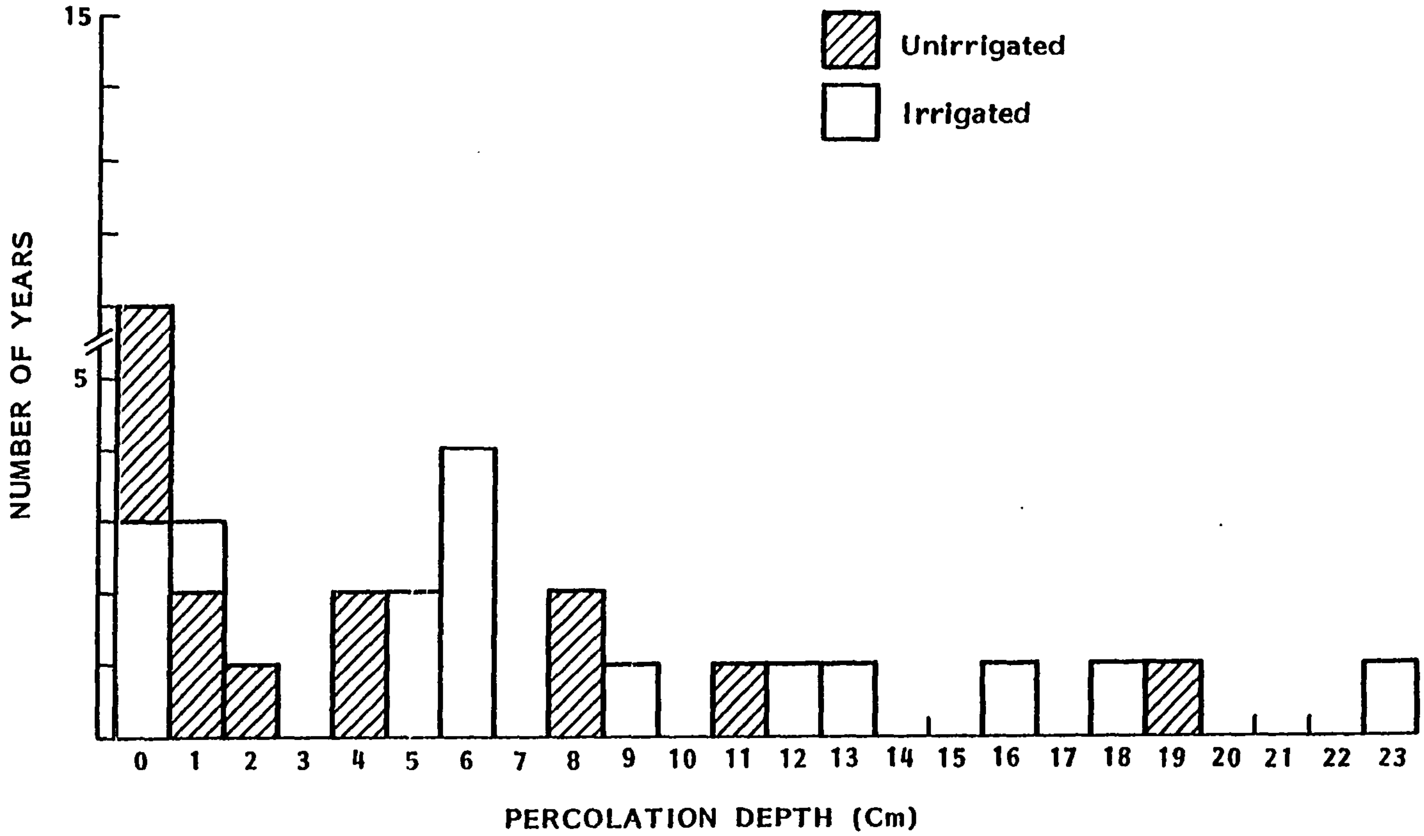


Figure 16. Distributions of total percolation in July, August, and September, at Cedar Rapids, Iowa, 1958-1977

Irrigation of a Sandy Soil in Southwest Minnesota

The original soil-moisture program (program number one) was run for two soils in southwest Minnesota (Lamberton). The two soils are Webster, which represents much of the soil at the experimental farm and has a high moisture capacity, and Dickman, which is a sandy type soil. The plant-available-moisture capacity values for these soils are given in Table 17. Soil-moisture values used to represent moisture conditions in the spring were based on data provided by the Soils Department, University of Minnesota.

Table 17. Plant-available-moisture capacity of Webster and Dickman soils near Lamberton, Minnesota

Depth in centimeters	Plant-available-moisture in centimeters	
	Webster	Dickman
0-30	3.45	3.60
30-60	4.23	2.80
60-90	4.92	1.20
90-120	5.97	1.20
120-150	6.07	1.20

Distribution of Irrigated Corn Yield and Yield Increase Due to Irrigation, Lamberton, Minnesota

In order to evaluate the response of corn yield to July, August and September irrigation, the original soil-moisture program was first run with the natural weather data, then rerun with the irrigation subroutine included. The unirrigated corn yield, the irrigated corn yield and the yield increase due to irrigation for both soils are summarized in Tables 18 and 19, and the distribution of yield increases due to irrigation are shown in Figures 17 and 18.

On the Dickman sand, the average yield with natural weather conditions was 5109 Kg/ha, and the average yield with irrigation was 9627 Kg/ha, slightly below the zero stress value of 9682 Kg/ha. The average yield increase due to irrigation was 4518 Kg/ha (Table 18). This is higher than for any of the Iowa locations. This would indicate a steep gradient of irrigation response as one moves north from northwest Iowa (see Figure 11). However, a considerable part of the effect is due to the moisture capacities of the soils used. At Doon, the available capacity was 22.6 centimeters in the 150 centimeter profile, while for the Dickman sand in southwest Minnesota, it was only 10 centimeters. One would expect comparable soils at these two locations to have comparable stress indices. The yield increase due to irrigation ranged from 330 to 9444 Kg/ha and was over 3000 Kg/ha in 13 of the 19 years (Table 18, Figure 17). The irrigation water applied ranged from 5 to 45 centimeters, with an average of 20 centimeters/ year.

For the Webster soil, the average unirrigated yield was 7509 Kg/ha, and with irrigation, the yield was 9653 Kg/ha, again slightly below the zero stress value of 9682 Kg/ha. The average yield increase due to irrigation ranged from 27 to 7541 Kg/ha (Figure 18, Table 19), and was over 3000 Kg/ha in 7 of the 19 years (Table 19). From the tables, it can be seen that in 1974, 1975 and 1976, when summer drought occurred in that portion of the Corn Belt, irrigation provided a major increase in yield on both the Dickman sand and Webster type soils. Generally, on the sandy soil,

Table 18. Unirrigated and irrigated corn yield and yield increase due to irrigation at Experimental Farm, Lamberton, Minnesota for the Dickman Sand

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1960	7692	9682	1990
61	7405	9682	2277
62	6885	9682	2797
63	8539	9557	1018
64	4197	9681	5484
65	5432	9682	4250
66	5778	9542	3764
67	2422	9682	7260
68	9352	9682	330
69	5621	9682	4061
70	3927	9678	5751
71	4051	9682	5631
72	9194	9682	488
73	3268	9594	6326
74	385	9512	9127
75	1827	9682	7855
76	0	9444	9444
77	5071	9438	4367
78	6027	9653	3626
Average	5109	9627	4518

Table 19. Unirrigated and irrigated corn yield and yield increase due to irrigation at Experimental Farm, Lamberton, Minnesota for the Webster Soil

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1960	9083	9682	599
61	8995	9682	687
62	9274	9682	408
63	9565	9595	30
64	8516	9682	1166
65	9155	9682	527
66	6303	9632	3329
67	9792	9682	2890
68	9306	9682	376
69	9070	9682	612
70	5991	9675	3684
71	7131	9680	2549
72	9651	9678	27
73	6345	9658	3313
74	5516	9565	4049
75	5479	9682	4203
76	2018	9559	7541
77	6160	9553	3393
78	8329	9677	1348
Average	7509	9653	2144

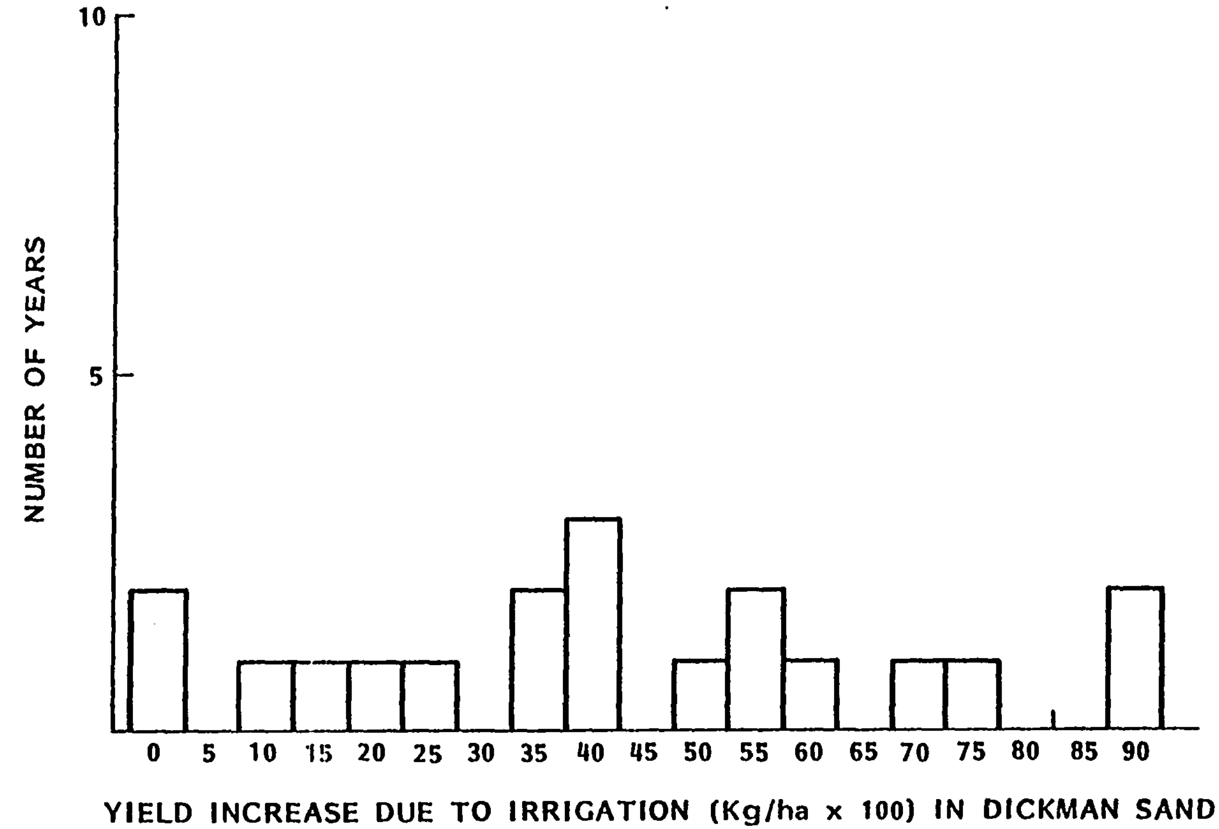


Figure 17. Distribution of yield increase due to irrigation of a Dickman sand at Lamberton, Minnesota, 1960-1978

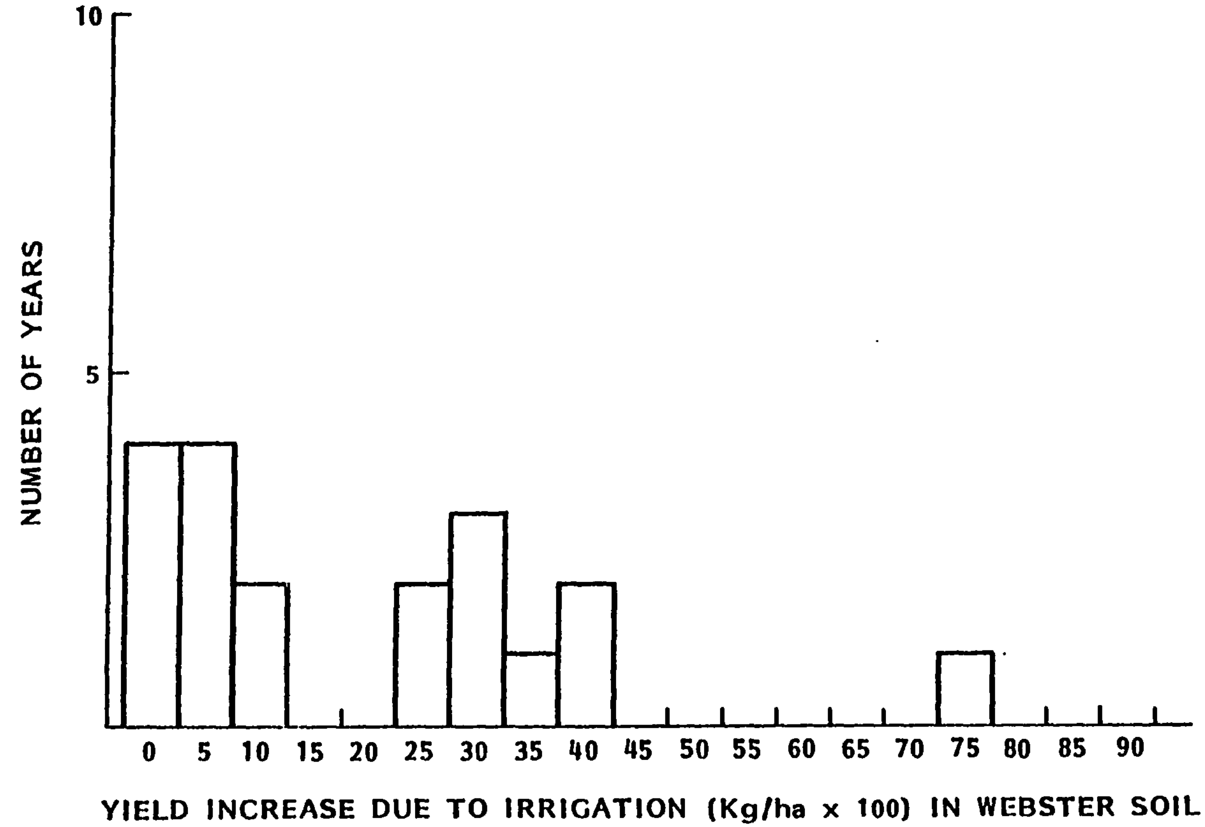


Figure 18. Distribution of yield increase due to irrigation of a Webster soil at Lamberton, Minnesota, 1960-1978

the yield response to irrigation is much higher than for the higher capacity Webster soil. The irrigation water applied to the Webster soil ranged from 10 to 42.5 centimeters/year and averaged 22.5 centimeters/year. Total irrigation applied on the Webster soil was slightly above that applied to the Dickman soil because of the much greater water holding capacity.

The results are typical of what should be expected on a low-moisture capacity soil and a high-moisture capacity soil in a region where rainfall is not in great deficiency. On a high-moisture capacity soil, normal rainfall provides a good soil-moisture reserve, and this reserve supply is enough to provide moisture through summer dry periods with only moderate yield reductions.

In a sandy soil, even though the profile may be at field capacity in the spring, it does not supply enough reserve for most summer weather, and the response to irrigation is higher and is significant in most years.

Irrigation of a Cisne Soil, Fayette County, Illinois

The programs were run for the Cisne soil, with a claypan at 61 centimeters or less, below the surface. The closest weather station for the rainfall and evaporation-pan data is Carlyle, so data from that location were used for the weather inputs. The moisture parameters used for the Cisne silt loam are given in Table 20.

Table 20. Plant available-water and saturation level of a Cisne silt loam in centimeters/15-centimeter increment

Depth in centimeters	Plant-available-water	Saturation level
0-15	3.30	4.17
15-30	3.30	4.55
30-45	3.30	4.55
45-60	2.33	3.67

Distribution of Irrigation Corn Yields and Yield Increase Due to Irrigation on a Cisne Soil, Fayette County, Illinois

The original soil-moisture program (program number one) and programs number two and three were run for the Cisne soil of Illinois in Fayette County. The years of record used were 1964-77, a total of 14 years. Since the actual starting soil-moisture values are not available, the program used here assumed field capacity in the spring. Thorne (M. Thorne, Dept. of Agronomy, Univ. of Illinois, personal communication, 1980) stated that the 152 centimeter profile in Illinois is rarely not at field capacity in the spring. Saturation data also were used to estimate the years when soil moisture was above the field capacity to start the spring period. The soil was considered impermeable to rooting below 60 centimeters, and deeper depths did not enter into the calculation. The summary of unirrigated and irrigated yields and also the yield increase due to irrigation in the original program, in program number two, and in program number three are shown in Tables 21, 22, 23, 24 and 25, respectively.

Table 21. Unirrigated and irrigated corn yield and yield increase due to irrigation at Carlyle, Illinois for the Cisne soil - data from original program

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1964	4250	9682	5432
65	5659	9682	4023
66	541	9648	9107
67	8960	9682	722
68	3802	9682	5880
69	6782	9682	2900
70	5568	9682	4114
71	3692	9682	4990
72	5122	9612	4490
73	4473	9682	5209
74	6237	9682	3445
75	5078	9682	4604
76	869	9682	8813
77	6799	9646	2847
Average	4845	9672	4827

Table 22. Unirrigated and irrigated corn yield and yield increase due to irrigation at Carlyle, Illinois - starting soil moisture at field capacity; data from program number two

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1964	2025	9682	7657
65	7283	9682	2399
66	1162	9678	8516
67	9664	9682	18
68	5028	9682	4654
69	8357	9682	1325
70	7171	9682	2511
71	6802	9682	2880
72	5150	9612	4462
73	6684	9682	2998
74	7899	9682	1783
75	6923	9682	2759
76	1066	9682	8616
77	7695	9680	1985
Average	5922	9677	3755

Table 23. Unirrigated and irrigated corn yield and yield increase due to irrigation at Carlyle, Illinois - starting soil moisture at saturation; data from program number two

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1964	3205	9682	6477
65	7283	9682	2399
66	1518	9682	8164
67	9664	9682	18
68	5028	9682	4654
69	8357	9682	1325
70	7171	9682	2511
71	6802	9682	2880
72	6189	9680	3491
73	6684	9682	2998
74	7899	9682	1783
75	7248	9682	2434
76	2203	9682	7479
77	8287	9682	1395
Average	6253	9682	3429

Table 24. Unirrigated and irrigated corn yield and yield increase due to irrigation at Carlyle, Illinois - starting soil moisture at field capacity; data from program number three

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1964	1668	9682	8014
65	6081	9682	3601
66	565	9652	9087
67	9464	9682	218
68	3763	9682	5919
69	7552	9682	2130
70	5933	9682	3749
71	4617	9682	5065
72	5150	9612	4462
73	5425	9682	4257
74	6441	9682	3241
75	5450	9682	4232
76	948	9682	8734
77	6870	9650	2780
Average	4995	9673	4678

Table 25. Unirrigated and irrigated corn yield and yield increase due to irrigation at Carlyle, Illinois - starting soil moisture at saturation; data from program number three

Year	Unirrigated yield Kg/ha	Irrigated yield Kg/ha	Gain due to irrigation Kg/ha
1964	1833	9682	7849
65	6209	9682	3473
66	587	9652	9065
67	9553	9682	129
68	3901	9682	5781
69	7694	9682	1988
70	6163	9682	3519
71	4713	9682	4969
72	5150	9613	4463
73	5720	9682	3962
74	6587	9682	3095
75	5525	9682	4157
76	948	9682	8734
77	6938	9652	2714
Average	5109	9673	4564

The original program was run in order to represent what would happen if the soil had an excellent drainage system. This program has not held any excess water in the profile and the average unirrigated yield was 4845 Kg/ha (Table 21), reflecting the considerable stress which occurred. The average yield increase due to irrigation was 4827 Kg/ha. The yields ranged from 722 to 8813 Kg/ha and were over 3000 Kg/ha in 11 of the 14 years examined (Table 21). The irrigation water applied in each year ranged from 12.5 to 40 centimeters, with an average of 24 centimeters.

Soil-moisture program number two was written for the situation that exists on the Cisne Soil. In this program, each increment is allowed to reach field capacity, then moisture above field capacity is added to each increment up to saturation from the bottom to the surface, and any moisture above this amount is assumed to run off the area. It is assumed that the claypan has zero percolation, so all moisture extraction is limited to the layer above the claypan. The average unirrigated yield was 5922 Kg/ha (Table 22) in the program in which starting soil moisture was at field capacity. This yield is higher than projected by the original program, because this program retains more water for longer periods since no percolation occurs, and moisture retained above field capacity helped reduce the moisture stress. The average yield increase due to irrigation was 3755 Kg/ha (Table 22). The yield increase ranged from 18 to 8616 Kg/ha and was over 3000 Kg/ha in 5 of the 14 years (Table 22). Irrigation water applied averaged 20 centimeters and ranged from 5 to 37.5 centimeters. In the same program, when saturation was assumed as the starting soil moisture, the average unirrigated yield was 6253 Kg/ha. The average yield increase due to irrigation was 3429 Kg/ha, yield increases ranged from 18 to 8164 Kg/ha and were over 3000 Kg/ha in 5 of the 14 years (Table 23). Irrigation water applied averaged 19 centimeters and ranged from 5 to 32.5 centimeters for individual years. The differences between a "field capacity" start and a "saturation" start were relatively small.

Soil moisture program number three allows the soil to reach saturation, then allows for percolation to occur. For the situation when the starting soil moisture was assumed to be at field capacity, the average yield under natural rainfall conditions was 4995 Kg/ha. This yield is higher than that projected by the original program because the soil remains above field capacity for a longer period, which reduces stress. The average yield increase due to irrigation was 4678 Kg/ha (Table 24). The yield increase due to irrigation ranged from 218 to 9087 Kg/ha and was more than 3000 Kg/ha in 11 of the 14 years (Table 24). Irrigation water applied averaged 22 centimeters and ranged from 7.5 to 37.5 centimeters. When the starting soil moisture was assumed to be at saturation, the average yield increase due to irrigation was 4564 Kg/ha (Table 25), very little different from that obtained with field capacity as the starting moisture. The yield increase due to irrigation ranged from 129 to 9065 Kg/ha and was more than 3000 Kg/ha in 11 of the 14 years (Table 25). Irrigation water applied averaged 22 centimeters and ranged from 7.5 to 37.5 centimeters.

Excess-moisture index was examined in soil-moisture programs number two and three. This index obtains an estimate of years when excess moisture would be a problem and it is calculated as the number of days between May 9 and July 1 when the mean air-filled pore-space of the top two 15-centimeter layers is less than, or equal to, 10 percent. Table 26 summarizes the excess index for soil-moisture programs number two and three.

Table 26. Annual excess-index values for the Cisne soil at Carlyle, Illinois; data from program numbers two and three

Year	Program number two		Program number three	
	Field capacity	Saturation	Field capacity	Saturation
1964	0	26	4	9
65	10	18	5	7
66	0	14	3	5
67	19	25	7	9
68	14	25	14	18
69	9	30	12	16
70	26	31	12	16
71	20	35	13	18
72	0	10	0	0
73	35	36	18	24
74	28	33	6	13
75	2	27	4	9
76	0	6	0	1
77	0	7	2	4
Average	12	23	7	11

In program number two, when the starting soil moisture was at saturation in the spring, the mean excess index was 23, and 86 percent of the years exceeded 9, and ranged from 6 to 36 days (Table 26). In the program in which the starting soil moisture was at field capacity, 50 percent of the time the excess index exceeded 9, and the average was near 12, and ranged from 0 to 35 days (Table 26). In the soil-moisture program number three, with the starting soil moisture at saturation, the mean excess index was near 11, and ranged from 1 to 24 days, with only 43 percent of the years exceeding 9 (Table 26). In the same program, when the starting soil moisture was at field capacity, the mean excess index was 7, and ranged from 0 to 18 days. It exceeded 9 in 36 percent of the years (Table 26). These results indicate that, as a minimum, in 36 percent of the years, excess moisture would reduce the yield potential because early growing-season excess moisture can cause problems in the Cisne soil.

The output from soil-moisture program number two was examined to obtain the number of years when soil moisture was at saturation. With field capacity as the starting value, 8 of the 14 years of data showed values of soil moisture above field capacity in some part of the profile (Table 27). Five years showed values of soil moisture reaching saturation in the second 15-centimeter layer for more than 9 days. These same five years also showed excess moisture occurring in the lower two 15-centimeter layers, with four years having more than 2 days of excess moisture (Table 27). In the same program, with the starting soil moisture at saturation, 7 of the 14 years showed values above field capacity for more than 9 days in both May and June in the second 15-centimeter layer (Table 28). These same 7 years also showed excess moisture occurring in the lower two, 15-centimeter

Table 27. Number of days in which soil moisture reached saturation at depths 0-15 and 15-30 centimeters (program number two); starting soil moisture at field capacity

Year		May		June		July		August		September	
	Depth	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
1964											
65				1	3						
66											
67			18	1	14	2	3		1		
68		4	9		8						
69				3	4	7	12				
70				6	18						
71			7	2	9						
72											
73		1	4	7	16						
74		1	1	3	23						
75											
76											
77											

Table 28. Number of days in which soil moisture reached saturation at depths 0-15 and 15-30 centimeters (program number two); starting soil moisture at saturation

Year		May		June		July		August		September	
	Depth	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
1964		3	26	1	4						
65		2	26	1	9						
66		5	26		13						
67		3	26	2	14	3	2		1		
68		8	26		8						
69		3	26	5	16	7	12				
70		3	26	9	21						
71		6	26	3	10						
72			26		6						
73		5	26	7	16		1				
74		3	26	3	23						
75		2	26	1	4						
76		1	26		6						
77		1	20								

layers for more than 2 days (Table 28). This shows that in soils such as the Cisne, with a claypan layer, excess moisture can be a problem and could delay planting and affect root development.

There are few actual data available to compare the results obtained here with field trial data. In December, 1980, the Illinois Irrigation Newsletter reported results of the four years (1977-80) on a Cisne type soil. Over the four years, an average yield increase due to irrigation of 4440 Kg/ha was obtained. Program number two, which is believed to represent the Cisne conditions most closely, gave an average yield increase of 3755 Kg/ha over the 14 years tested. An irrigation yield of 11,525 Kg/ha was reported in 1980. Surface and subsurface drainage gave yield increases of 1889 to 2519 Kg/ha over the 4 years. In a dry year, there was some indication that drainage reduced yields. The excess-moisture index calculated here would indicate that, overall, drainage would be beneficial. In a 2-year study on a reclaimed mine soil, Loveland (1980) estimated that for each unit the excess index was above 9, yield was decreased 629 Kg/ha. Applying that value to the excess index calculated using program number two, with a starting value at field capacity, the average reduction due to excess moisture was 3900 Kg/ha. Characteristics of the reclaimed mine soil and the Cisne are greatly different, and the comparison is for an index versus a field-drainage system. A drainage system could probably not remove all the effects of excess moisture. If it removed two-thirds of the effect, the results would be comparable. Drainage, and irrigation, are both needed if the shallow Cisne type soil is to produce maximum yields.

THE EFFECT OF IRRIGATING THE COARSE TEXTURE SOIL ON WATER RESOURCES IN IOWA

About 5 percent of Iowa's soils are considered to be coarse textured or low water-holding soils. As has already been discussed, these soils should give the highest response to irrigation. The distribution of coarse textured soils in Iowa is shown in Figure 19. Table 29 lists the area covered by these soils in each county. From Figure 19 it can be seen that the highest concentration of coarse textured soils extends from north-northeastern Iowa through east central Iowa.

There are several ways to determine how much water is used to irrigate an area. One common method to calculate the water used is to multiply the number of hectares irrigated by the number of centimeters water applied and multiply by 100 to obtain the number of cubic meters of water applied. In Table 30, the estimated amount of water needed for irrigation of low water-holding capacity soils in Iowa is given. The data compiled in columns 1 and 2 of this table are derived from Tables 29 and 15, respectively. The results listed in column 3 of Table 30 indicate that the north-central, northeast and east-central sections of Iowa require the highest amount of water, if they are to be irrigated. By far the greatest use of water for irrigation has been in the northwestern and west central parts of the state where irrigation is concentrated mostly on the bottomlands of the Missouri River. Expansion of irrigation should be expected in other parts of the state due to higher crop and land prices and drought in recent years. This expectation is backed by the marked increase in the application for irrigation permits received by the Iowa Natural Resources Council in

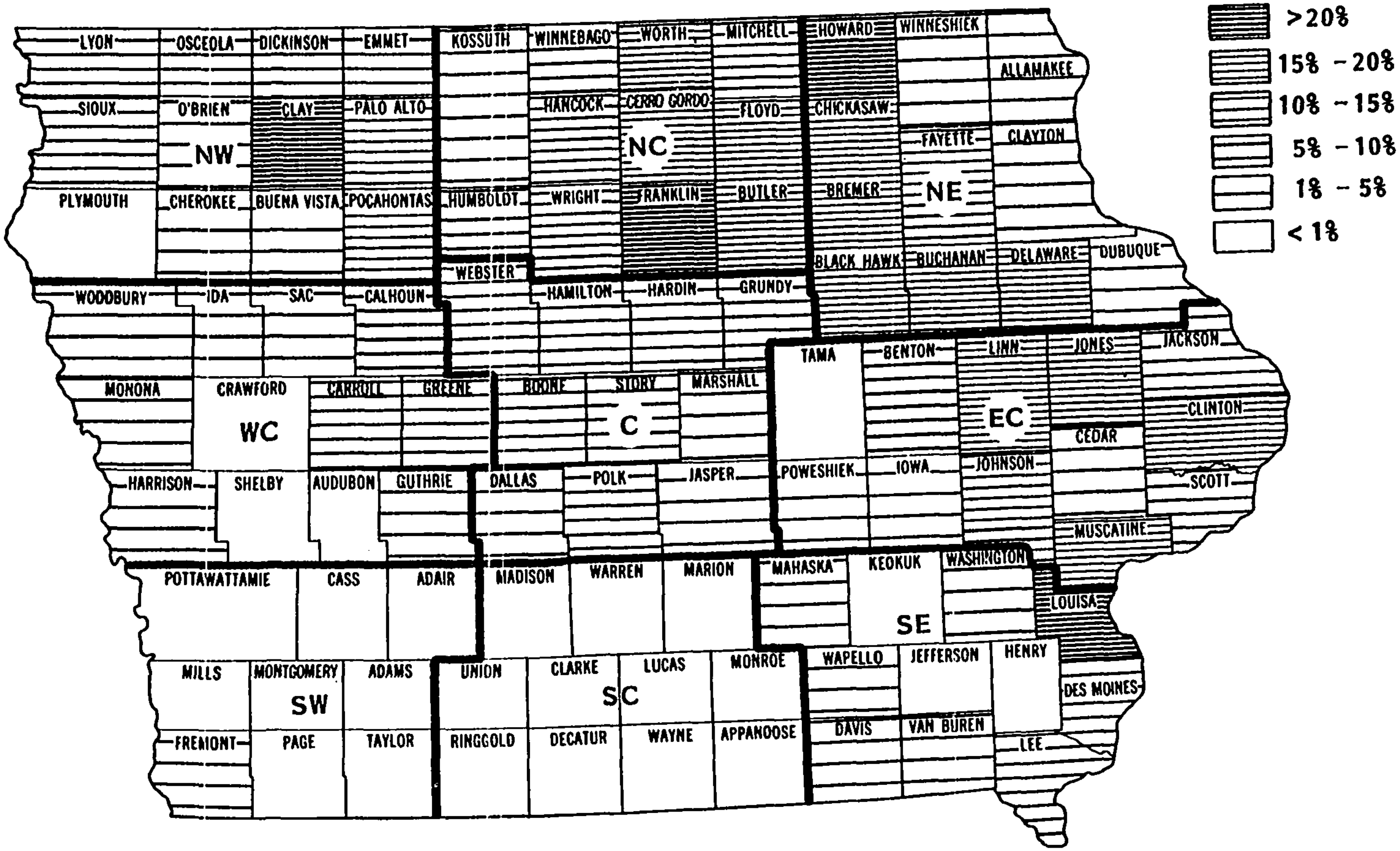


Figure 19. Percentage of low water-holding capacity soils by county (Iowa Geological Survey, 1976)

Table 29. Percentage and the area of coarse textured soils in Iowa, by county

County and district	Land in farms[a] hectares (1000)	% of coarse textured soils	Area of coarse textured soils hectares (1000)
NW District			
Buena Vista	144	1	1.44
Cherokee	145	1	1.45
Clay	141	15	21.15
Dickinson	91	5	4.55
Emmet	97	5	4.85
Lyon	149	5	7.45
O'Brien	144	1	1.44
Osceola	99	5	4.95
Palo Alto	140	10	14.00
Plymouth	219	--	--
Pocohontas	145	10	14.50
Sioux	190	5	9.50
TOTAL			85.28
NC District			
Butler	144	20	28.80
Cerro Gordo	134	20	26.80
Floyd	125	20	25.00
Franklin	143	15	21.45
Hancock	143	10	14.30
Humboldt	108	5	5.40
Kossuth	246	1	2.46
Mitchell	118	10	11.80
Winnebago	100	5	5.00
Worth	99	20	19.80
Wright	146	10	1.46
TOTAL			162.27

[a]Source: Iowa Department of Agriculture, 1981.

Table 29. *Continued*

County and district	Land in farms[a] hectares (1000)	% of coarse textured soils	Area of coarse textured soils hectares (1000)
NE District			
Allamakee	155	1	1.55
Black Hawk	118	20	23.60
Bremer	107	20	21.40
Buchanan	142	20	28.40
Chickasaw	126	20	25.20
Clayton	186	1	1.86
Delaware	143	20	28.60
Dubuque	144	1	1.44
Fayette	181	10	1.81
Howard	119	15	17.85
Winneshiek	172	1	1.72
TOTAL			153.43
WC District			
Audobon	114	--	--
Calhoun	142	5	7.10
Carroll	144	5	7.20
Crawford	183	--	--
Greene	144	5	7.20
Guthrie	150	1	1.50
Harrison	175	1	1.75
Ida	111	1	1.11
Monona	174	1	1.74
Sac	146	1	1.46
Shelby	151	--	--
Woodbury	210	1	2.10
TOTAL			31.16

Table 29. *Continued*

County and district	Land in farms[a] hectares (1000)	% of coarse textured soils	Area of coarse textured soils hectares (1000)
C District			
Boone	136	5	6.80
Dallas	144	1	1.44
Grundy	128	5	6.40
Hamilton	144	5	7.20
Hardin	142	5	7.10
Jasper	183	1	1.83
Marshall	141	1	1.41
Polk	106	5	6.30
Story	136	5	6.80
Webster	173	5	8.65
TOTAL			53.93
EC District			
Benton	177	5	8.85
Cedar	143	1	1.43
Clinton	166	20	33.20
Iowa	147	1	1.47
Jackson	159	5	7.95
Johnson	137	10	13.70
Jones	146	20	29.20
Linn	159	20	31.80
Muscatine	102	20	20.40
Poweshiek	147	1	1.47
Scott	98	5	4.90
Tama	181	--	--
TOTAL			154.37

Table 29. *Continued*

County and district	Land in farms[a] hectares (1000)	% of coarse textured soils	Area of coarse textured soils hectares (1000)
SW District			
Adair	147	--	--
Adams	109	--	--
Cass	142	--	--
Fremont	129	1	1.29
Mills	110	--	--
Montgomery	106	--	--
Page	134	--	--
Pottawattamie	229	--	--
Taylor	137	--	--
TOTAL			1.29
SC District			
Appanoose	117	--	--
Clarke	107	--	--
Decatur	133	--	--
Lucas	106	--	--
Madison	143	--	--
Marion	125	--	--
Monroe	108	--	--
Ringgold	137	--	--
Union	106	--	--
Warren	140	--	--
Wayne	130	--	--
TOTAL			--

Table 29. *Continued*

County and district	Land in farms[a] hectares (1000)	% of coarse textured soils	Area of coarse textured soils hectares (1000)
SE District			
Davis	126	1	1.26
Des Moines	88	5	4.40
Henry	106	--	--
Jefferson	108	--	--
Keokuk	144	--	--
Lee	120	5	6.00
Louisa	96	15	14.40
Mahaska	143	1	1.43
Van Buren	120	1	1.20
Wapello	102	1	1.02
Washington	141	1	1.41
TOTAL			31.12
Totals for state	13,678.86		672.85

Table 30. Volume of water needed to irrigate the low water-holding capacity soils in Iowa

District	Area of coarse textured soils hectare (1000)	Irrigation water applied (cm)	Volume of water needed million cubic meters
Northwest	58.28	22.0	128.2
West Central	31.16	18.5	57.6
Southwest	1.29	19.5	2.5
North Central	162.27	18.0	292.0
Central	53.93	18.5	99.8
Northeast	153.43	15.5	237.8
East Central	154.37	14.0	216.1
Southeast	31.12	15.5	48.2

recent years (Table 31). Iowa Natural Resources Council data indicate that by 1980 only 0.8 percent of the state was under irrigation. The estimated total water use for irrigating this much area is about 360 million cubic meters per year, or a little more than 5 percent of the state's annual total water withdrawal. In 1980, the total estimated water withdrawal for the state was about 6770 million cubic meters.

Sources of Water for Irrigation

A study of growth of irrigated lands in Iowa shows a significant growth of irrigation since 1975. Irrigated farms have increased from 36,800 hectares in 1967 to 89,000 hectares in 1979 (Table 32). Among the upper midwestern states, Iowa ranks last in the growth of its irrigated

Table 31. Trends in irrigation permits issued by the Iowa Natural Resources Council with the projection for the year 2000[a]

Year	Authorized permits	Authorized irrigated area hectares	Water authorized to use million cubic meters/year
1969	649	39,000	120
1976	837	53,000	177
1977	1429	93,000	340
2000	4000	299,000	900

[a]Source: Iowa Natural Resource Council, 1978.

lands. For example, irrigated areas in Minnesota have increased from 10,000 hectares in 1967 to 180,000 hectares in 1979. Illinois had 12,000 hectares of lands under irrigation which had increased to 50,000 hectares in 1979. In 1977, about 66,800 hectares were irrigated in Iowa with the sources of water as follows:

Surface water	Stream	13,400	hectares
	Reservoir	6,000	hectares
Ground water	Wells	47,400	hectares

To measure the impact of irrigation on the water resources in Iowa, the availability of both surface and ground water in the area of irrigation needs to be investigated.

Table 32. Growth of irrigated lands in Iowa

Year	Area irrigated hectares (1000)	Percent change
1967	36.8	+ 3
1968	37.6	+ 2
1969	38.4	+ 2
1970	32.4	-17
1971	26.3	-19
1972	20.2	-23
1973	18.2	-10
1974	24.3	+33
1975	38.4	+58
1976	53.0	+39
1977	66.8	+25
1978	72.8	+ 9
1979	89.0	+22
1980	112.6	+27

Surface Water Availability

Not all of the water flowing in Iowa's streams is available for irrigation, or other uses. Water withdrawals from some streams are not permitted because the protected flow of streams does not allow removal of water during drought, which is also the time when irrigation is needed the most. The state's regulations require that when the flow at any location on a river is equal to, or less than, 84 percent duration flow, water cannot be withdrawn. The 84 percent duration flow is the regulated "protection flow" for streams and rivers in Iowa. Flow duration is represented as a curve, discharge versus percent of time, and shows the percent of time that flow is equal to or greater than various rates during the period under consideration.

Average annual runoff in Iowa varies from less than 5 centimeters in the northwest part of the state to over 20 centimeters in the most eastern section (Figure 20). The average annual runoff over the state is about 15 centimeters. These figures do not include the flows of the Mississippi and Missouri rivers. Total annual flow for Iowa's streams amounts to 22 billion cubic meters. It has been estimated that the potential yield, or the water in excess of protected flow, is about 17 billion cubic meters per year (Iowa Natural Resources Council, 1978). This much water is associated with the high flow period during the months of summer. To make this water available for withdrawal by irrigation, a system of reservoirs and ponds would need to be developed.

Ground Water Availability

Ground water resources always have been one of the optimum solutions to water supply problems. More attention is being diverted to ground water as the need for water increases. Effective management of ground water requires a good knowledge about its availability. Ground water availability is highly related to the geographical structure and formation of the region where the water is to be used. Aquifer geology can be described and classified into the unconsolidated (unconfined) and bedrocks (confined).

Ground water in Iowa occurs in a variety of both unconsolidated and bedrock aquifers. The most significant of these aquifers are alluvial and glacial outwash sand and gravel deposits, glacial drift, and the

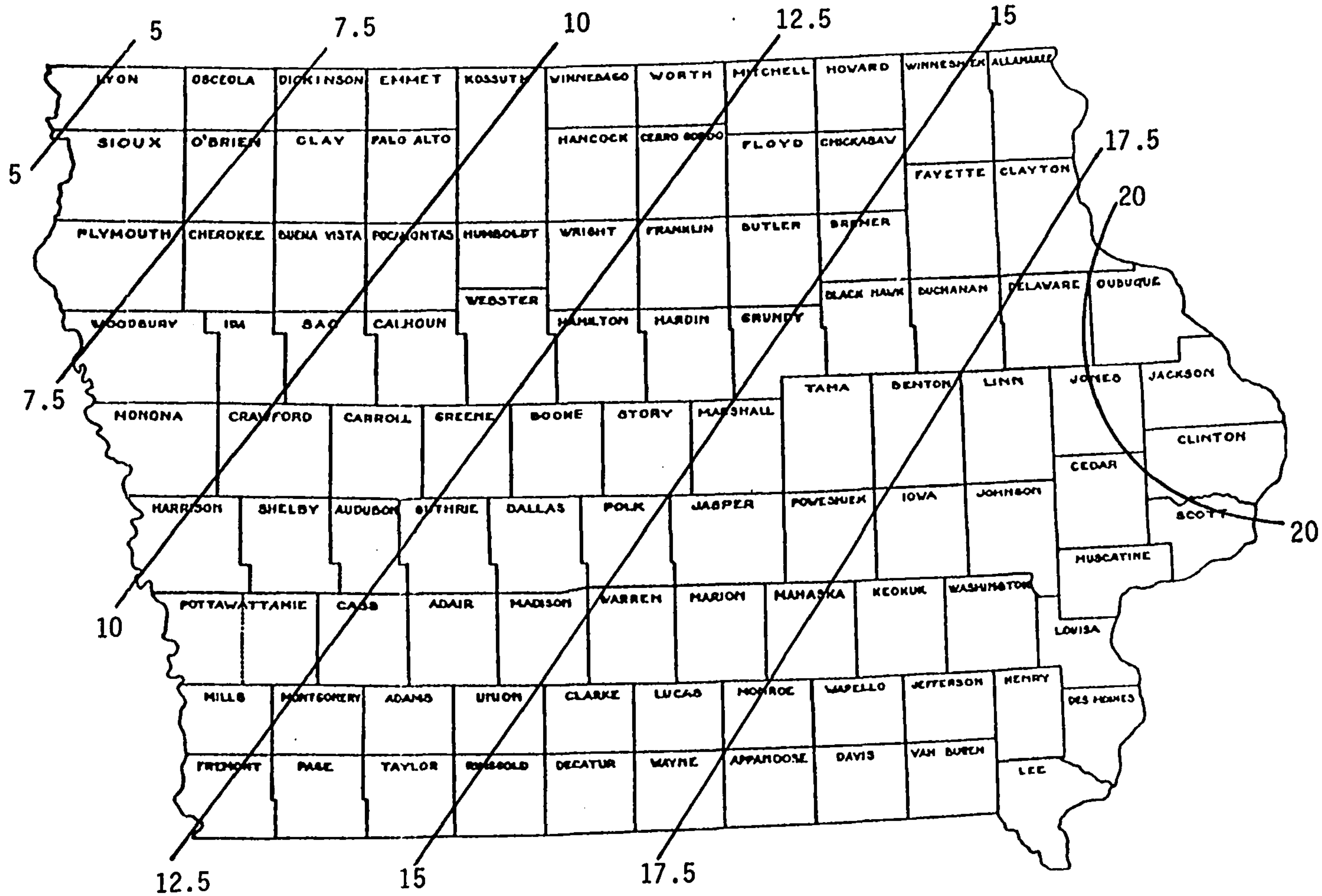


Figure 20. Average annual runoff (cm) in Iowa (Iowa Natural Resources Council, 1978)

limestone, dolomite, and sandstone formations. The productivity of an aquifer is different from place to place in the state. Ground water availability from a particular aquifer in a particular spot cannot necessarily be measured by the ground water yield of different aquifer systems. Although the above statement is logical, a rough estimate of the above storage volume of different aquifer systems in the region and the amount of recharge into these systems can provide an excellent background to decide if enough water could be provided for irrigation.

Unconsolidated, coarse-grained sediments, such as well-sorted sand and sandy gravel, have the greatest capacity for both storage and transmitting water; and, accordingly, they make the most productive aquifers. Unconsolidated, fine-grained sediments such as silt and clay may have a storage capacity as great as that of the coarse-grained sediments, but they transmit water much less readily.

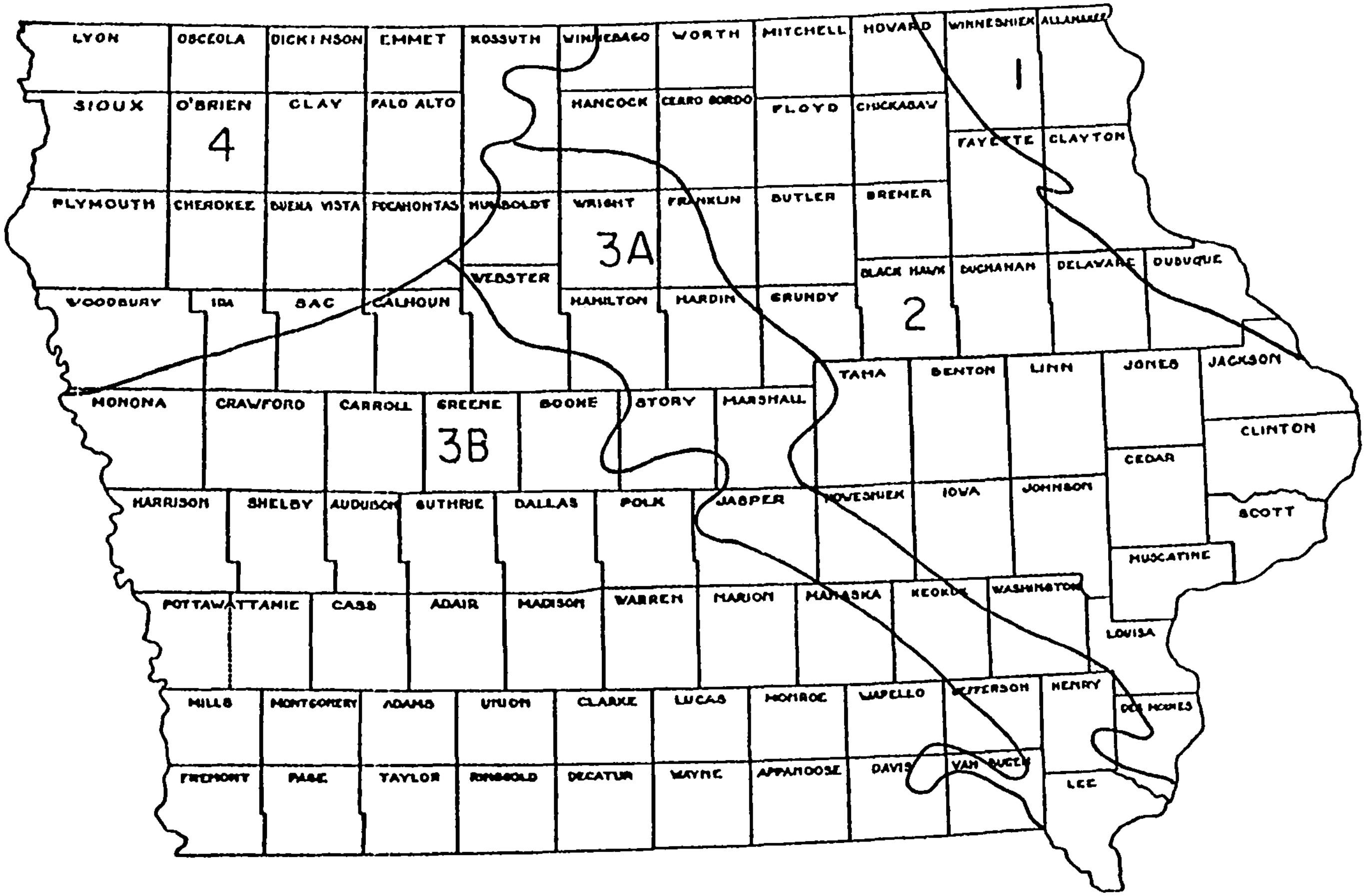
Glacial drift consists mostly of water-sorted permeable sand and gravel to form an important aquifer in Iowa. The unsorted portions of glacial drifts are mostly impermeable till. In the average locality, wells in the glaciated region are generally more successful than in the unglaciated areas. In Iowa, the thickness of glacial drift over most of the state is generally less than 30 meters, and comparatively small quantities of water can be obtained. However, the drift helps to recharge aquifers in the bedrock below it and sustain the base flow of streams. The most productive ground-water aquifers are associated with glacially derived outwash sand and gravel. Pre-glacial bedrock valleys and buried channels in central and east central Iowa frequently are connected with overlying alluvial aquifers, and the two systems function as a single productive aquifer. The extent and the amount of water sorted in the different glacial aquifers, and the recharge to the system, are listed in Table 34.

In addition to glacial and bedrock aquifers, alluvial deposits along the Mississippi and Missouri rivers and interior streams are sources of large volumes of ground water. Large water users in Iowa currently depend on alluvial sands and gravels as sources of water supply.

Bedrock aquifer systems in Iowa have not been actively mined, as in other places in the country. The quantity of water available to wells from bedrocks varies widely, in accordance with the hydrologic characteristics of the underlying rocks. The generalized bedrock of Iowa consists of Dakota Sandstone, Mississippi and Pennsylvanian Silurian-Devonian, and Combro-ordovician (Figure 21). Table 34 summarizes the storage and annual recharge estimates for these major aquifers in Iowa, along with the estimates for glacial aquifers.

The Impact of Irrigating the Low Water-Holding Capacity Soils in Iowa

As was stated in the first section of this discussion, the amount of water required for irrigation of coarse textured soils in Iowa ranges between about 290 million cubic meters in the north central part of the state to almost zero in southwest and south central portions of the state. It was shown in the sections on surface water and ground water availability that the propsective for a water supply for irrigation is promising. There are about 17 billion cubic meters of surface water available each year which could be used for irrigation, by providing a system of storages throughout the state. A more reliable and promising source of water is



1 - Cambro-Ordovician
2 - Silurian-Devonian
3A - Mississippian
3B - Pennsylvanian Subcrop
4 - Northwest Bedrock

Figure 21. Generalized bedrock of Iowa (Iowa Geological Survey, 1973)

Table 34. Storage volume of different aquifer systems in Iowa[a]

Aquifer system	Storage (billion cubic meters)		
	Confined	Unconfined	Glacial
1. Cambro-ordovician (lower bedrock)	1.2-2.4	2.4-8.5	0.07-0.4
2. Silurian-Devonian (middle bedrock)	7.3-12	24-97	1.2-85
3. Mississippian (upper bedrock)	0.4-8.5	12-48	0.4-2.4
Pennsylvanian Subcrop			0.7-3.6
4. Northwest bedrock (Dakota sandstone)	0.4-8.5		1-4.8

[a]Sources: 1) Iowa Geological Survey (1973).
2) Iowa Natural Resources Council (1978).

Annual recharge (billion cubic meters)			Accumulated storage from surface to deepest formation (billion meters^3)
Confined	Unconfined	Glacial	
0.05-0.4	0.06-0.6	0.02-0.2	2.5-8.9
0.005-0.2	0.4-3.6	0.1-1.2	26.4-129.5
0.004-0.2	0.1-1.2	0.001-1.2	20.9-86.4
		0.2-2.4	9.6-48.1
0.001-0.04		0.1-1.2	10.3-57.8

the ground water. The last column in Table 34 shows that for every section of the state, there are underground storage areas of water ranging from at least 2.5 billion in the northeast to possibly as high as 130 billion cubic meters in the central part. Recalling that the most water required for irrigation of sandy soils is something less than 300 million cubic meters, about one tenth of the least ground water storage, the impact of irrigation of these soils seems not to have any adverse effect on Iowa's water resources. However, any final statement needs more in-depth hydrological research. Along with that, the agricultural economist should study the cost-benefit analysis of exploring these sources of water. The results of such studies may not recommend the mining of the water at the present time, because it is not economically feasible. Even if this is the case, the progressing technology and management of water resources and the rising price of agricultural products in the future may make it possible to turn to irrigation in the future.

Problems of Water Management and Allocation

If the water for irrigating the low moisture-holding soils was the only water to be used in the state of Iowa, there would not be any problem. But despite the fact that Iowa is a water-rich state overall, due to uneven distribution and spread of water resources, at least for the moment, many areas within the state face some problem with regard to water supply for irrigation and other uses.

Competition among different users is a major problem in allocating or using more water for a particular user, for example, irrigation. Iowa industrial and municipal supplies are the major competitor to Iowa agriculture. Since the water used by industry is not highly consumed and returns to streams, the competition is not that controversial. The major conflict exists between the public supplies and irrigation. Tables 35 and 36 give estimates for water use and competition between the users in Iowa. As these tables show, municipal users are highly competitive, especially in the use of ground water resources that might be used for irrigation, and vice versa.

Table 35. Water uses in Iowa 1000 cubic meters per day, 1975[a]

Use	Ground water	Surface water	Total	% of total — Ground	% of total — Surface
Irrigation	2611	1741	4352	57	14
Public supplies	818	303	1121	18	2
Industry	700	10780	11480	15	84
Livestock	356	83	439	8	*[b]
Rural Domestic	80	*	80	2	*
Total	4565	12907	17472		

[a]Source: Iowa Natural Resources Council (1978).

[b]* = Negligible.

One principal problem with Iowa streams is that though their average flow is higher than the amount of water used, the summer-fall flows are very low. This problem could be resolved if the water of high-flow periods of spring and early summer were stored, providing adequate water for the users. Major problems with ground water sources are the depth and areal

Table 36. Trends in Iowa Natural Resources Council permitted wells by use[a]

Year	Irrigation	Municipal	Others	Total
1960	585	519	252	1356
1965	622	718	246	1586
1970	756	788	476	2020
1975	975	870	621	2466
1980	1963	1239	729	3931

[a]Source: Iowa Natural Resources Council (1981).

location. These two problems, plus the quality of water, limits its use in many places over the state. Depth causes the cost of water withdrawal to run high and makes it economically unfeasible for some users, such as irrigation, to use that water.

Surface water and ground water are primary sources of water. Precipitation is also considered a primary supply for the agricultural areas where irrigation is not practiced too often. When it becomes hard to utilize these primary supplies of water, then the secondary sources of water start to be used. The secondary supplies are municipal effluent, industrial waste and agricultural return flows. The Iowa Natural Resources Council in recent years has stated in their public statements that the state must intensify its efforts to develop storage, and resist any massive withdrawals from alluvial ground water and streams, other than for domestic, ordinary agricultural and municipal purposes. The interior alluvial aquifers and streams of the state cannot support massive consumptive withdrawals of water. Storage reservoirs are the only viable answer to the increasing industrial demands for water in the interior of Iowa.

Three major regions in Iowa which are facing problems with both surface and ground water resources are: Northwest, Southwest and South-central. In many parts of these areas, it is impossible to impose any additional withdrawal demands on water for any kind of use, particularly irrigation, which is a highly consumptive use. Problems of water shortages are not limited to the drought periods, but even under nondrought conditions, there are water supply shortages (Iowa Natural Resources Council, 1981). Thus, choosing an area, such as any one of the three regions, for irrigation when they already are facing problems of water withdrawal, would be meaningless for this study. For this reason, Central Iowa, with its problem of water shortages, at least for the present being limited to dry years, seems to be an appropriate location for the analysis.

Geographical Characteristics of Central Iowa

The land in Central Iowa, although disected by many small streams, is flat to gently rolling. The highest altitudes are in the north, about 381 meters above mean sea level (MSL) and the lowest are in the south, with an altitude of about 236 meters. There is also a gradual tilt toward the east. For this reason, the major streams of central Iowa flow to the southeast. The surface areas on the north are mostly flat, or gradually sloped. The lands in the south and southeast part of Central Iowa are disected and offer many potential sites for dams and artificial reservoirs and lakes. Natural lakes are more prevalent in the northern part of

Central Iowa. The major rivers in this area are the Des Moines, Boone, Skunk, and Iowa rivers (Figure 22).

Surface Water

Stream

Average stream flows in Central Iowa vary with the size of the drainage area; the larger the size of the drainage basin, the larger the number of tributary streams which deliver water to the major rivers. The size of the drainage area increases downstream. The downstream portions of the rivers have larger drainage areas and the flows are higher. The flow in the Des Moines River almost doubles from upstream to downstream of Des Moines. The annual average flow is 57 cubic meters per second above Des Moines and 108 cubic meters per second below Des Moines, where it is joined by the Raccoon River. Figure 23 shows the schematic of stream flow in the major rivers in Iowa.

Monthly stream flow is highest from March through June, and lowest from August or September through January. Table 38 gives details about the flow of streams of Central Iowa. As it appears from this table, the Des Moines River basin is the largest in Central Iowa. The Skunk, Iowa, and Cedar rivers are the next in order of size. Considerable variation between the lowest flow and highest flow can be observed in all rivers. There are also streamflow fluctuations from year to year. These year-to-year fluctuations are due to weather changes. For example, the long-term average stream flow in the Des Moines River is about 57 cubic meters per second. In 1951, the average stream flow in this river was 150 cubic meters per second, while in 1956 it was only 6 cubic meters per second.

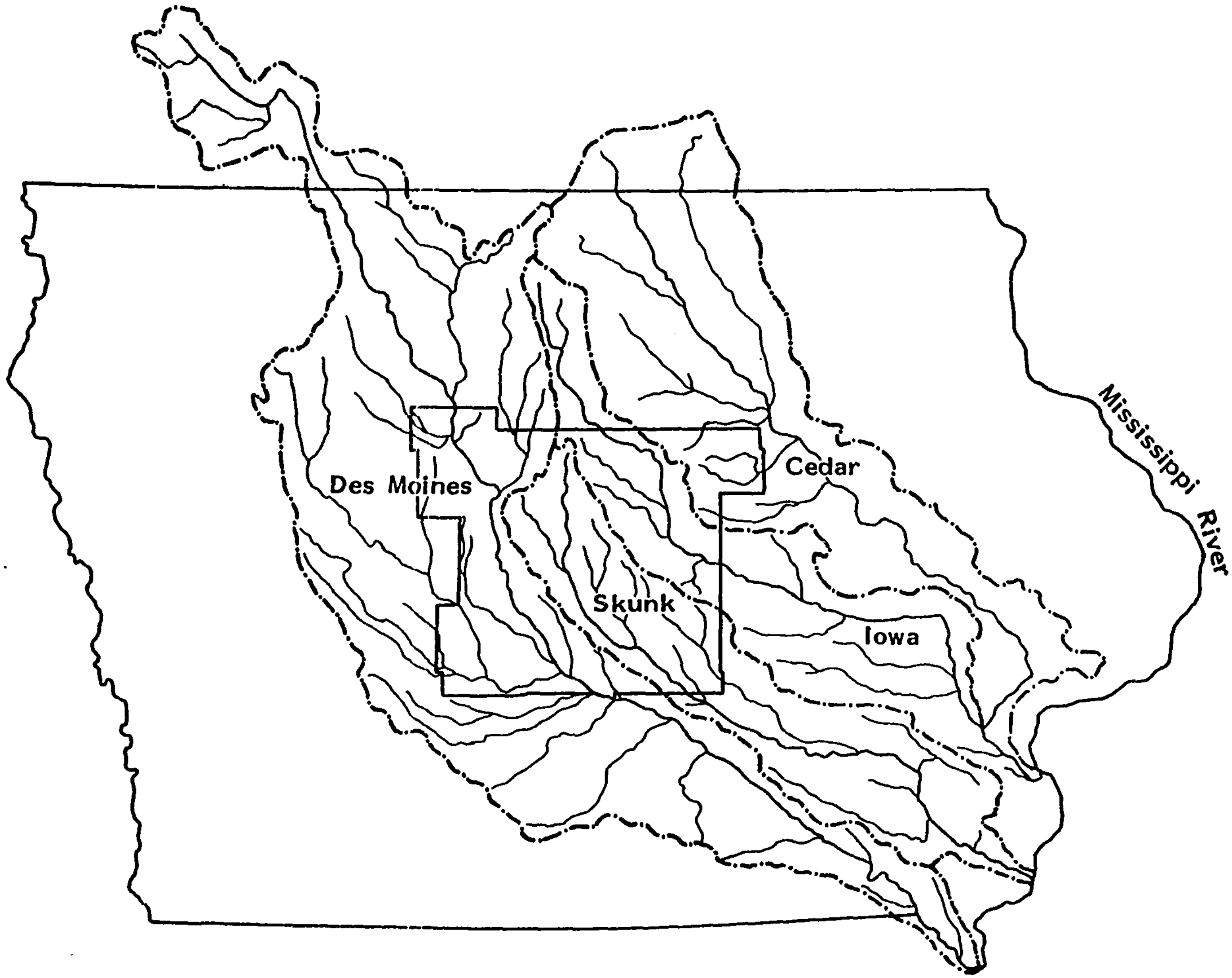


Figure 22. Major rivers of central Iowa (Iowa Geological Survey, 1965)

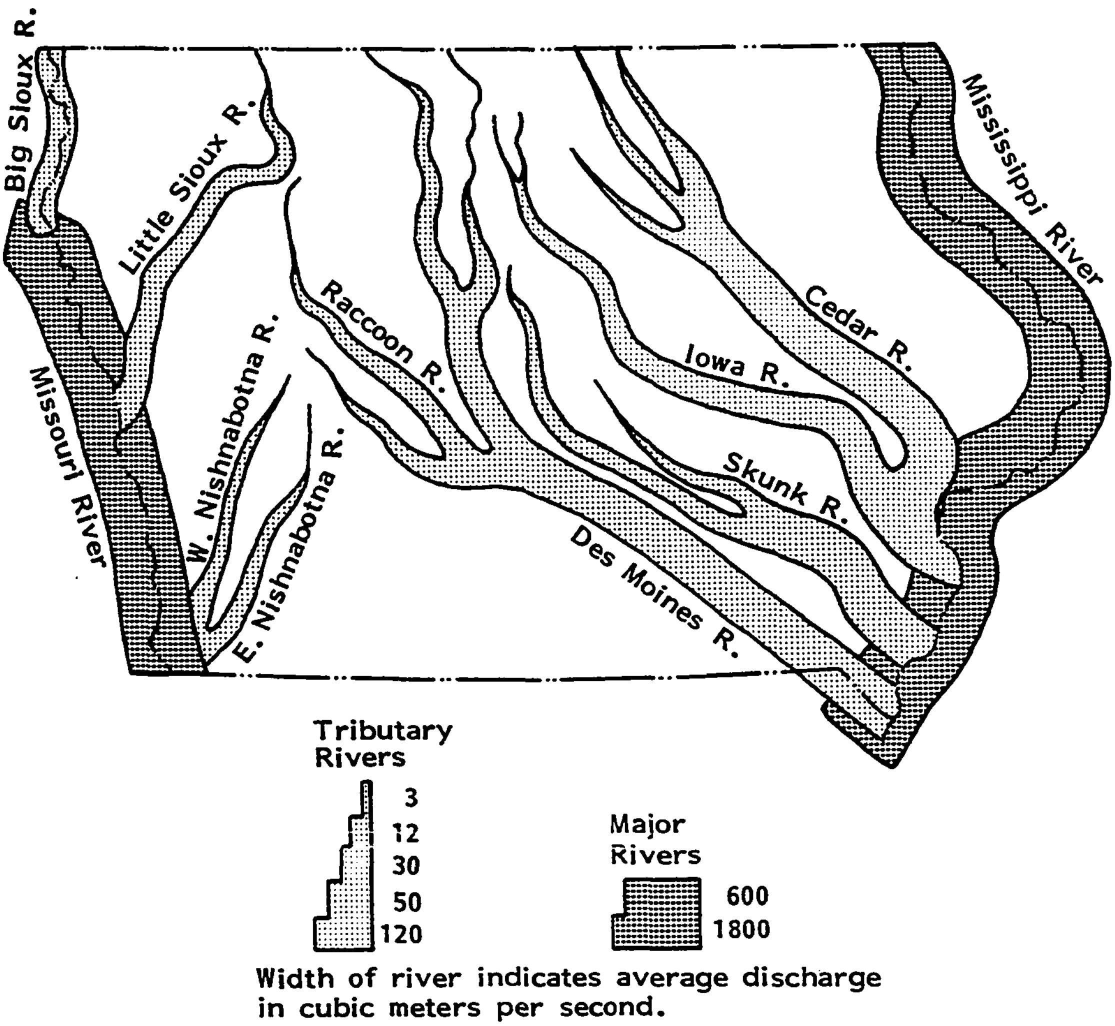


Figure 23. Stream flow in the major rivers in Iowa (Iowa Natural Resources Council, 1978)

Table 38. The streams flow characteristics of Central Iowa[a]

Stream	Lowest daily mean m^3/sec	Highest daily mean m^3/sec	Maximum peak discharge m^3/sec	Average discharge m^3/sec	Drainage area (sq Km)
Cedar River Basin					
Blackhawk Creek at Hudson	0.05	212	255	3.0	785
Iowa River Basin					
Iowa River near Rowan	0.08	216	240	4.7	1111
Iowa River at Marshalltown	0.25	1116	1190	20.1	4051
Skunk River Basin					
Skunk River near Ames	0.00	163	244	3.6	816
Skunk River near Oskaloosa	0.05	410	566	21.4	4235
North Skunk River near Sigourney	0.00	657	779	10.7	1891
Des Moines River Basin					
Des Moines River at Fort Dodge	0.40	963	1003	36.0	10852
Boone River near Webster City	0.04	552	575	9.3	2186
Des Moines River near Boone	0.48	1583	1626	44.1	14273
Des Moines River at Des Moines	0.68	1674	1705	56.0	16175
North Raccoon River near Jefferson	0.02	657	825	17.7	4193
South Raccoon River at Redfield	0.54	436	991	11.7	2559
Raccoon River at Van Meter	0.28	935	1167	33.2	8912
Des Moines River below Raccoon River at Des Moines	1.56	1863	2180	106.3	23256

[a]Source: Iowa Geological Survey (1965).

Stream flow in 1956 was among the lowest ever recorded. The same problem was observed in other Central Iowa areas for the year of 1956. The Iowa River, whose long-term average is about 20 cubic meters per second, showed only an average flow of 3 cubic meters per second in 1956. This situation was due to intensive drought over the region. Annual precipitation during 1955 was about 25 centimeters below normal at Ames. A preview of what could be expected if Iowa were faced with a drought was given by the severe, but short, drought of 1976-77.

Flow characteristics of Central Iowa streams

Flow-duration curve representing stream flow measuring stations in Central Iowa, based on the daily flows of a 20-year period (1956-1975) is plotted in Figure 24. The flatter duration curves are associated with relatively heavier rainfall, bigger drainage areas, and the presence of alluvial and bedrock aquifers along the river valleys, or near the surface. Note that the alluvial channels are easily recharged by rainfall and overland flow, and are a ready source contributing to base flow during dry periods. The United States Geological Survey Water Resources Division in Iowa has calculated many flow duration curves over the state. Curves are moderately flat for streams in the eastern part of the state and relatively steep for streams in the western part. The steeper flow-duration curves for streams in the western and south central parts of the state indicate the greater variability of flow with time. Because of the smaller streams of the western and south-central part of the state, the flow is mainly due to direct runoff after precipitation. In the eastern part of

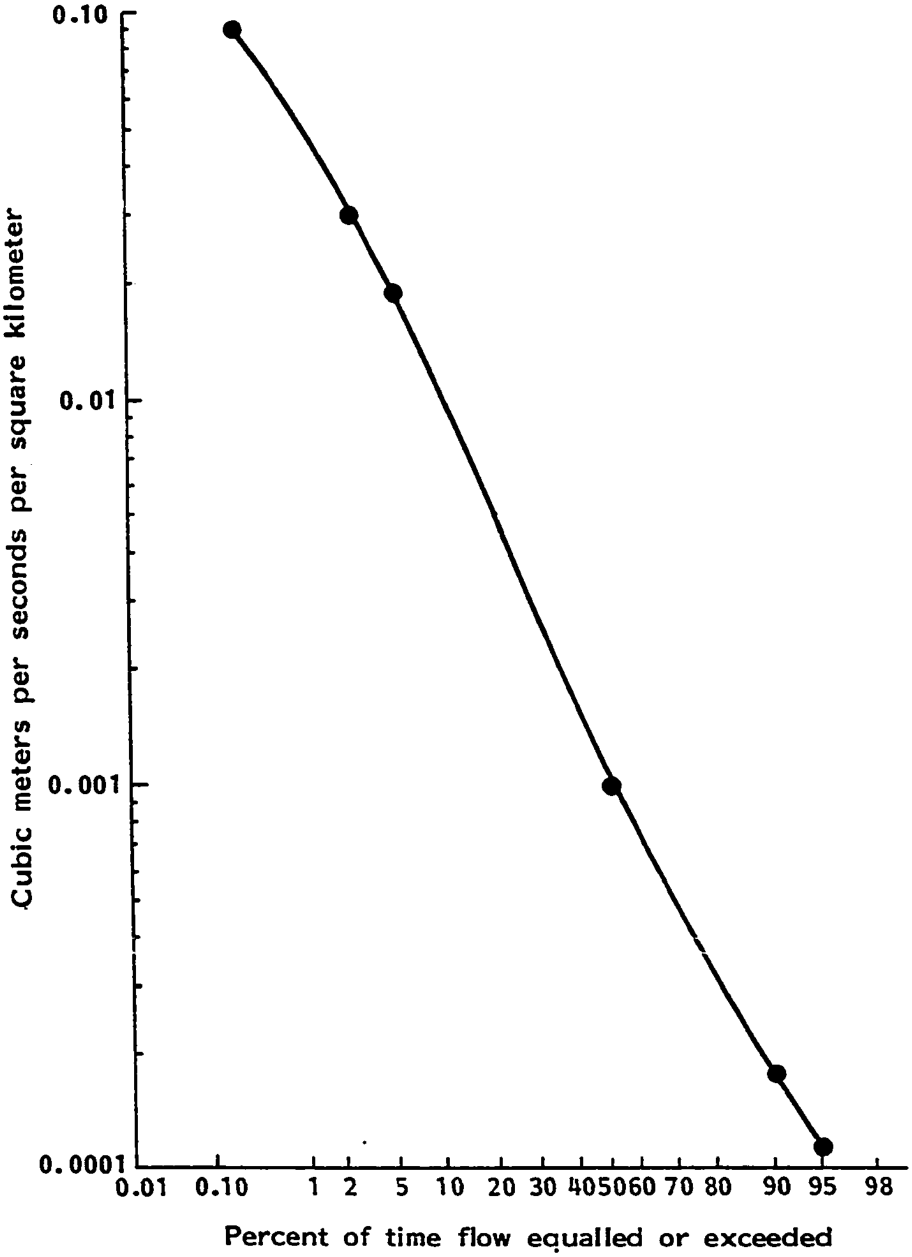


Figure 24. Stream flow duration curve for Central Iowa (Iowa Natural Resources Council, 1976)

the state, much of the base flows to the streams are supplied by bedrock aquifers which are more consistent.

Runoff

The average runoff in the smaller drainage basin in Central Iowa is about 0.005 cubic meters per second per square kilometer. If this average amount of water was available from streams each day of the year, a water shortage would not occur. Water may become scarce, however, during periods when runoff is low. The average low-flow runoff during September, 1956, was less than 0.0002 cubic meters per second per square kilometer compared to the average of 0.005 cubic meters per second per square kilometer.

Ground water

Central Iowa is underlain by several aquifers. The aquifers at, or near, the surface through most of the area are composed of irregular layers of unconsolidated rocks and are referred to as the surficial aquifers. Table 39 summarizes the information about the aquifer systems in Central Iowa. Figure 25 also gives a three-dimensional view of these aquifer systems.

Water availability from Central Iowa aquifers

The amount of water that aquifers in Central Iowa will yield varies not only from aquifer to aquifer, but within each aquifer. In the surficial aquifers, the sand and gravels in the alluvial aquifer are the best source of water. The possible production of water in alluvial aquifers along the major streams in Central Iowa ranges between 0.4 to 2 cubic

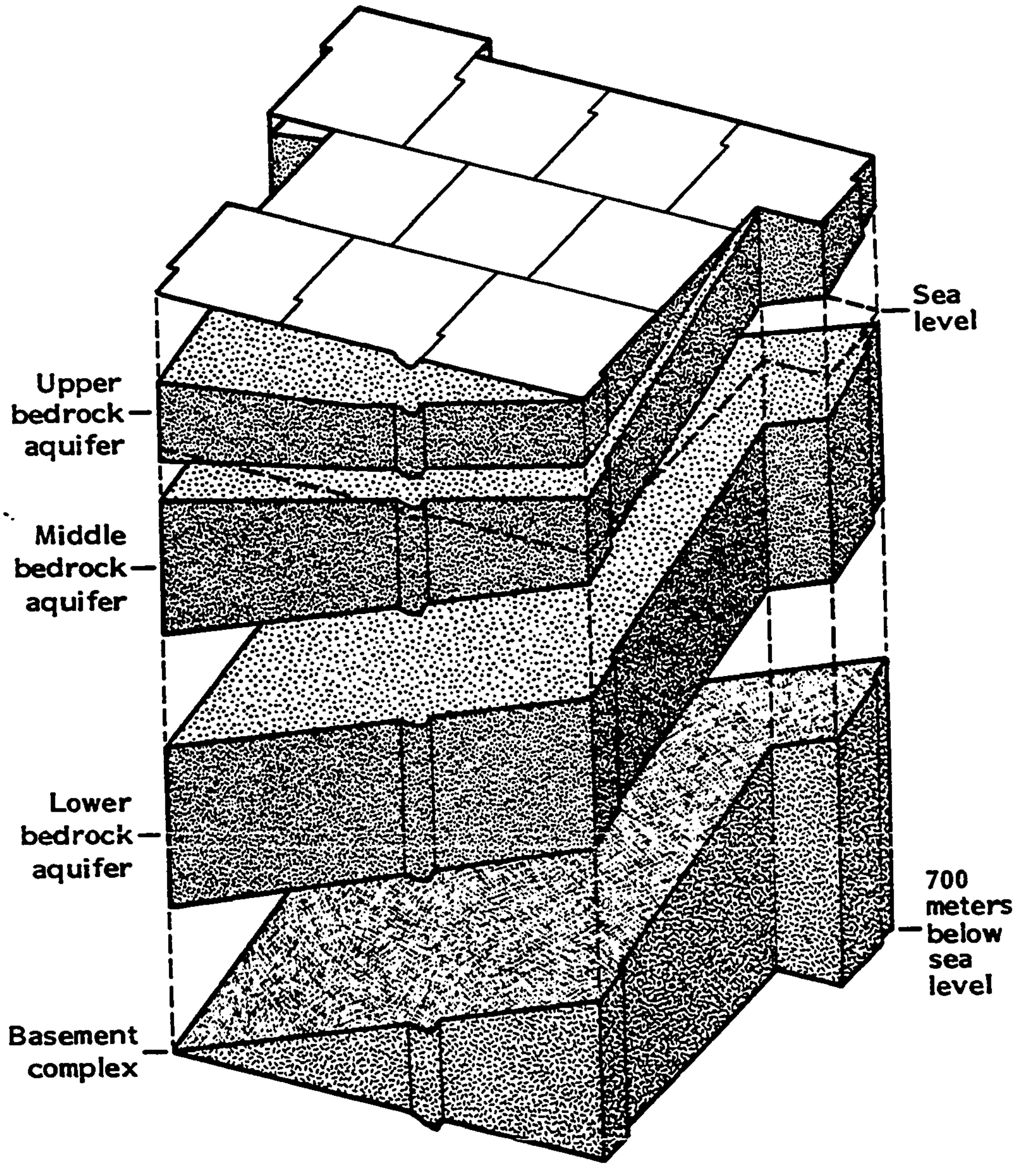


Figure 25. Aquifer system of Central Iowa (Iowa Geological Survey, 1965)

Table 39. Summary of aquifer characteristics[a]

Aquifers	General thickness (meters)
Surficial Alluvial Buried-channel Drift	0-110
	0-270
Upper bedrock	0-140
	2-60
Middle bedrock	120-220
	100-210
Lower bedrock (includes Jordan sandstone)	110-170
	105-160

[a]Source: Iowa Geological Survey (1965).

meters per minutes, and higher. The alluvial aquifers in the southern half of Central Iowa, including Dallas, Polk, and Jasper counties are the most productive and their possible production is mostly above 2 cubic meters per minute.

The upper and middle bedrock aquifers in Central Iowa often yield large amounts of water where they lie near the land surface. The productivity of this aquifer is highest, above 4 cubic meters per minute, in the northeastern and northwestern corner of Central Iowa. Yields from the lower bedrock aquifer are influenced by the thickness of the Jordan sandstone and the fractures and solution channels in the thick carbonate rocks which overlie it. Yields from this aquifer are greatest, over 4 cubic meters per minute, in the northern and eastern parts of the area where the Jordan sandstone is thickest.

Irrigation Water Requirement for Low Water-Holding Capacity Soils in Central Iowa

Table 40 includes the area of land in farms by each county in Central Iowa, as well as the maximum and minimum amount of the area with coarse textured soil within each county. The total area in this part of the state which may have this type of soil ranges between 53,000 to 120,000 hectares. Both of these estimates can be used to examine the dry conditions, such as of 1976 and 1977, to determine the amount of water needed to irrigate this type of soil in the Central Iowa region. By reviewing the preceding chapters of this discussion about water resources and availability in this region, a picture of the practicality of the irrigation of sandy soils or all soils in this part of Iowa can be given. Historical data about irrigation water applied, generated from the computer program model for sandy soils near Ames, are shown in Table 41. For the average situation, the amount of irrigation water applied is about 19 centimeters. For a dry year such as 1976, this amount was 38 centimeters, or twice that of the average. If the coarse textured soils of Central Iowa are to be irrigated in normal years, about 100 to 222 million cubic meters of water is needed. This amount would be about 200 to 450 million cubic meters for a dry year such as 1976. In contrast, if the whole area would be irrigated, the amount of water for both a normal year and a dry year, such as 1976, would be 2650 million cubic meters and 5300 million cubic

Table 40. Minimum and maximum area of coarse textured soils in Central Iowa

County	Land in farm hectares (1000)	% of coarse textured soil		Area of coarse textured soil hectares (1000)	
		Minimum	Maximum	Minimum	Maximum
Boone	136	5	10	6.80	13.6
Dallas	144	1	5	1.44	7.2
Grundy	128	5	10	6.40	12.8
Hamilton	144	5	10	7.20	14.4
Hardin	142	5	10	7.10	14.2
Jasper	183	1	5	1.83	9.1
Marshall	141	1	5	1.41	7.1
Polk	106	5	10	5.30	10.6
Story	136	5	10	6.80	13.6
Webster	173	5	10	8.65	17.3
Total	1433			52.93	119.9

Table 41. Computer generated data of irrigation water applied near Ames, Iowa

Year	Centimeters applied	Year	Centimeters applied	Year	Centimeters applied
1958	7.5	1965	20.0	1972	10.0
1959	15.0	1966	27.5	1973	15.0
1960	12.5	1967	20.0	1974	22.5
1961	12.5	1968	15.0	1975	22.5
1962	17.5	1969	12.5	1976	37.5
1963	12.5	1970	22.5	1977	27.5
1964	12.5	1971	27.5		
				Total	370.0
				Mean	18.5

meters, respectively. To satisfy the water needed for irrigation of this area, both primary sources of water must be carefully studied before any conclusive decision can be made. Due to seasonal and uneven distribution of streamflows in Central Iowa, it is necessary to develop a reservoir and pond system whicn can handle the water requirements for irrigation. The number of farm ponds in Central Iowa and their capacity are given in Table 42. The storage volume of these ponds for each county are checks against the maximum water needed to irrigate the coarse textured soil of that county in a dry year such as 1976. The results are shown in Table 43. Note that the amount of water needed to irrigate these soils was estimated from the computer model to be 37.5 centimeters for Ames. This value was used to calculate the volume of water required for irrigation, listed in Table 43. As it appears in Table 43, storage capacity of existing ponds can only satisfy a very small fraction of what would be needed if a severe drought occurs. Average annual runoff for Central Iowa is about 15 centimeters (Figure 20). This amount was used to calculate the volume of annual runoff in Table 43.

Total annual flow for this part of Iowa is 2.15 billion cubic meters, or almost 10 percent of the state's total runoff. This much water seems to be enough to help both irrigation and ground water recharge in central Iowa, if an effective management of water resources takes over. The average annual runoff from Central Iowa is almost five times of what is needed for irrigating the coarse textured soils of this area.

In addition to surface water, unexplored aquifer systems of Central Iowa can be considered as a promising source of water supply for irrigation. The most-mined aquifer in Iowa is the unconsolidated system whose

Table 42. Farm ponds in Central Iowa, 1974[a]

County	Number of ponds	Surface area hectares	Storage volume cubic meters (1000)
Boone	243	147	900
Dallas	367	223	1360
Grundy	8	3	20
Hamilton	6	2	15
Hardin	30	12	90
Jasper	937	569	3470
Marshall	174	104	640
Polk	450	273	1665
Story	103	62	380
Webster	20	16	150

[a]Source: Iowa Natural Resources Council (1976).

Table 43. Maximum water requirement to irrigate low moisture-holding soils in Central Iowa by county, and existing reservoir capacities

County	Maximum area of coarse textured soil hectares (1000)	Water needed in dry year million m^3	Pond storage volume million m^3	Average annual runoff volume million m^3
Boone	13.6	51	0.90	204
Dallas	7.2	27	1.40	216
Grundy	12.8	48	0.02	192
Hamilton	14.4	54	0.02	216
Hardin	14.2	53	0.09	213
Jasper	9.1	34	3.50	275
Marshall	7.1	27	0.64	211
Polk	10.6	40	1.70	159
Story	13.6	51	0.38	204
Webster	17.3	65	0.15	260
Total	120.0	450	8.8	2150

exploration has doubled in 1980, compared to 1970 (Table 44). Too much use of this aquifer system may cause water problems, as it did during the water shortage in Ames in 1976. Attention should be directed to the Jordan aquifer, whose low quality makes it less favorable for municipal users, and thus less competitive for irrigation use.

Table 44. Trends in Iowa Natural Resources Council permitted wells by aquifer

Aquifer	1960	1970	1980
Unconsolidated	976	1318	2770
Dakota sandstone	39	74	139
Upper bedrock	54	111	129
Middle bedrock	106	183	339
Lower bedrock	165	265	320
Jordan	122	194	234
Total	1462	2145	3931

Overview

The crop-irrigation requirement is that portion of the consumptive use which must be supplied by irrigation. It is the consumptive use less the effective precipitation. Precipitation is effective only to the extent that it remains in the soil until the growing season and is available to plants. It would be necessary to determine monthly increments of the crop irrigation requirement in order to design a distribution system within the area of consideration which is capable of delivering the water required in the period of highest demand. Such monthly data for Central Iowa can be obtained from the data produced by the computer model developed in this study. Data shown in Table 45 are monthly crop irrigation requirements for Ames in 1976.

Table 45. Monthly irrigation water requirements for Ames, Iowa, 1976

Month	Irrigation requirement, cm
May	0
June	0
July	17.5
August	12.5
September	7.5
Total	37.5

Data in Table 45 are important because they provide the decision-makers in water management of the area with detailed information about the largest consumptive use for water irrigation. The monthly data are important where it is necessary to make an emergency plan for a short period of time in the case of unpredicted water shortages. These shortages are enhanced if the competitive users are in the high ranks of priorities. One example is the water shortage of mid-summer 1977, when the City of Ames in Iowa had to come up with an emergency plan.

Whatever the amount of water supply is for a given month, it must be reduced by the amount listed in Table 45 for the same month in order to find out how much water is left after irrigation for other uses. In this case, it should be decided what are the primary sources of water supply. The two major sources discussed in preceeding sections in this study are ground water and surface water. One can expect to use both sources if the supply from each individual source is not physically or economically adequate. If irrigation is going to be practiced in Central Iowa, and if the only source of water is preferred to be ground water, unless the deeper aquifer (Jordan aquifer) has not been mined, the problem is to be experienced with such practice. A problem of using only buried aquifers, or the upper aquifer in Central Iowa, has been observed on several occasions. An example is the heavy drawdown in the City of Ames wells during the drought of 1977. The wells in this city do not penetrate into the Jordan aquifer because of the low water quality it gives for drinking water.

One point of concern in using ground water as a source for irrigation is that, in most cases, the only competitors are municipal users and industry. If the water management is set such that the first priority is given to the municipal users and industry, since they are mostly nonconsumptive users and return their effluent back to the environment, that effluent can be used as a source of water for irrigation downstream. The only problem with this suggestion at the present time is the lack of economic feasibility. As water becomes more scarce in the future, and the need for irrigation remains the same, or becomes higher due to the higher demand for more food (which is a product of higher population), the use of effluent becomes more reasonable. Before the ground-water levels in an area decline enough to make pumping uneconomical, such as happened during the 1977 drought in Central Iowa, several things need to be done:

1) Alternative sources of water must be developed;
2) Artificial recharge must be exercised; and
3) Water using activities must be relocated.

In the absence of appropriate water-conserving measures, the increasing costs related to the greater pumping lifts could force abandonment of irrigated cropping, if no other source of water at reasonable cost is available. Irrigation represents a form of ground-water demand much greater than other uses.

The problem of irrigation in Central Iowa becomes more visible if the source of water is considered to be the surface water. The problem is magnified because, unlike the ground water, the competitors in using the surface water are larger in number.

The major water resource priorities in Central Iowa are:

water supply for irrigation;

municipal and industry uses;

flood plain management and control;

water quality;

fish and wildlife;

recreation.

Water supply and quality is related to both ground water and surface water. Flood plain management, fish and wildlife, and recreation are restrictively surface water uses and create additional conflict in water allocation problems.

Competing offstream uses of water for agricultural, domestic, and industrial needs, coupled with associated environmental and instream-flow uses, result in problems. These problems are either quantity related like stream-depletion, or quality related. Quality related problems, such as water pollution, can be enhanced by the lack of a sufficient quantity of water in streams. Extensive development of irrigated agriculture could strain the riverine ecosystems and, when protection for aquatic ecosystems is lacking, could severely threaten fish and wildlife dependent on the river flow. With increasing offstream and instream demands for water, it must be recognized that competition for water is a fact, and unless solutions are found, some restrictions can be expected to be imposed on use and development of water for some beneficiaries, such as irrigation.

Although competition for water refers primarily to surface water, in some locations in Central Iowa like Ames, ground and surface water supplies are interrelated. Depletion in one source in these areas results in more pressure on the other source. In this situation, surface and ground water represent a single resource with different characteristics. A volumetric analysis of the consumptive and nonconsumptive water uses in relation to water supply needs to be examined in order to measure the adequacy of flow for instream uses. Data in column 2 of Table 43 are important in this aspect because they represent the amount of water that would be consumed in Central Iowa in a dry year such as 1976.

Since irrigation in Central Iowa, as well as the rest of the state, is a supplementary application, the water used should be considered 100 percent as consumptive use. Consumption of water in some respects is more critical than the total quantity withdrawn for use because consumed water is not available for downstream uses or for ground-water recharge. If the majority of water in Central Iowa streams was imponded and part of that allocated for supplementary irrigation, based on information provided in earlier sections, use of a well-planned management system should provide adequate water for both irrigators and other users. The mineral-rich streams of Central Iowa (there are significant levels of nitrites in Iowa streams coming from farmlands by runoff) would also provide some of the nutrition required for crops.

Regarding the data presented in previous chapters, there is a tendency to draw water for irrigation more from the ground-water sources than from surface-water sources. This is done because of convenience problems and lack of adequate reservoir volumes to support irrigation, as well as other uses. Based on presented data, about 60 percent of the total water withdrawn for irrigation comes from ground water. (The total water withdrawn according to permits issued by Iowa Natural Resources Council in 1975 was 4.35 million cubic meters per day, with 2.60 million cubic meters coming from ground water (Table 35)). The remaining 40 percent is supplied by surface water. If it is assumed that the percentage of water use from each source remains the same, the amount of water which is taken from the streams and surface runoff for irrigation would change to that given in Table 46. The difference between the volume of water needed for irrigation, and the volume of surface runoff in Central Iowa, is the volume of of water remaining for the other uses. If this were controlled through reservoir routing and proper management, the supply seems adequate to satisfy all other categories for whatever the present needs are. The water resources planning for the future needs is a very dynamic phenomena and requires up-to-date reviewing and adjustment. It is also different from location to location. Simulated models such as what was developed for this study are useful if they are modified to fit the given physical characteristics of the area where the water plan is to be developed.

Table 46. Consumptive use of surface water by irrigation in coarse textured soils of Central Iowa by county, in million cubic meters

County	Surface water needed in dry year such as 1976	Annual runoff volume	Water remaining for other uses
Boone	20	204	184
Dallas	11	216	205
Grundy	19	192	173
Hamilton	22	216	194
Hardin	21	213	192
Jasper	14	275	261
Marshall	11	211	200
Polk	16	159	143
Story	20	204	184
Webster	26	260	234
Total	180	2150	1970

SUMMARY

A soil-moisture program developed by Shaw (1963) has been used to determine a weighted seasonal-stress index. This weighted seasonal-stress index was used in a regression equation to estimate corn yield. By including an irrigation cycle in the program, the response to irrigation was simulated.

Eight sites were chosen to evaluate the effect of irrigation on corn yield on low moisture-capacity soils in Iowa. Summary of the results obtained in this part of the study shows that the maximum yield increases due to irrigation are less in eastern than central and northwest Iowa. The average yield increases ranged from 822 Kg/ha at Cedar Rapids to 3261 Kg/ha at Doon. The greatest irrigation amounts were applied in northwest Iowa (Doon), and the least amounts were applied in eastern Iowa.

The soil-moisture program was run for two soils, Webster and Dickman, in southwest Minnestoa (Lamberton). On Dickman sand, the average yield increase due to irrigation was 4518 Kg/ha, and for the Webster soil, the average yield increase due to irrigation was 2144 Kg/ha. On the sandy Dickman soil, the yield response to irrigation is much higher than for the higher capacity Webster soil.

The original program was modified to represent conditions existing at the Cisne soil in Fayette County, Illinois. In the first modified program, program number two, excess moisture above field capacity gradually filled each layer until the first layer reached saturation. In the second modified program, program number three, daily rainfall filled each layer

to saturation and a subroutine was constructed to allow for downward movement for water until field capacity is reached.

The extraction pattern was modified to fit the situation with a claypan layer at the depth of 60 centimeters as exists in the Cisne soil. A simple loop was added to both modified programs which computed an excess index. Since the actual starting soil-moisture values were not available, the programs used here assumed field capacity in the spring. Saturation data also were used to estimate the years when soil moisture was above the field capacity to start the spring period. The following are a summary of the results obtained in this part.

The original soil-moisture program was run in order to represent what would happen if the soil had an excellent drainage system. The average yield increase due to irrigation was 4827 Kg/ha.

Soil-moisture program number two was written for the situation that exists on the Cisne soil. The average yield increase due to irrigation was 3755 Kg/ha in the program in which starting soil moisture was at field capacity. In the same program, when saturation was assumed as the starting soil moisture, the average yield increase due to irrigation was 3429 Kg/ha.

Soil-moisture program number three allows the soil to reach saturation, then allows for percolation to occur. For the situation when the starting soil moisture was assumed to be at field capacity, the average yield increase due to irrigation was 4678 Kg/ha. When the starting soil moisture was assumed to be at saturation, the average yield increase due to irrigation was 4564 Kg/ha.

Since soil-moisture program number two retains more water for longer periods, because no percolation occurs, it showed less stress than soil-moisture programs three or one.

The differences between a "field capacity" start and a "saturation" start were small.

Soil moisture program number two, with field capacity as the starting values, showed excess moisture occurring in the lower 15-centimeter layer more than 2 days in four years. In the same program with the starting soil moisture at saturation, excess moisture occurs in the lower two 15-centimeters for more than 2 days in seven years.

In 36 percent of the years, excess moisture would reduce the yield potential because early growing-season excess moisture can cause problems in the Cisne soil.

A summary of all data and information previously presented in the discussion about irrigation of sandy soils in Central Iowa is shown in Figure 26. The positive parameters in this model are stream inflow, ground water supply, and excess rainfall, or runoff. These are considered to be the supply part of the model. Consumptive use by irrigation, and the protective minimum low flow in streams are the negative parameters of this setup.

The maximum amount of water needed for supplementary irrigation in a dry year, such as that of 1976 in Central Iowa, is 450 million cubic meters. For a normal year, this amount is about 220 million cubic meters.

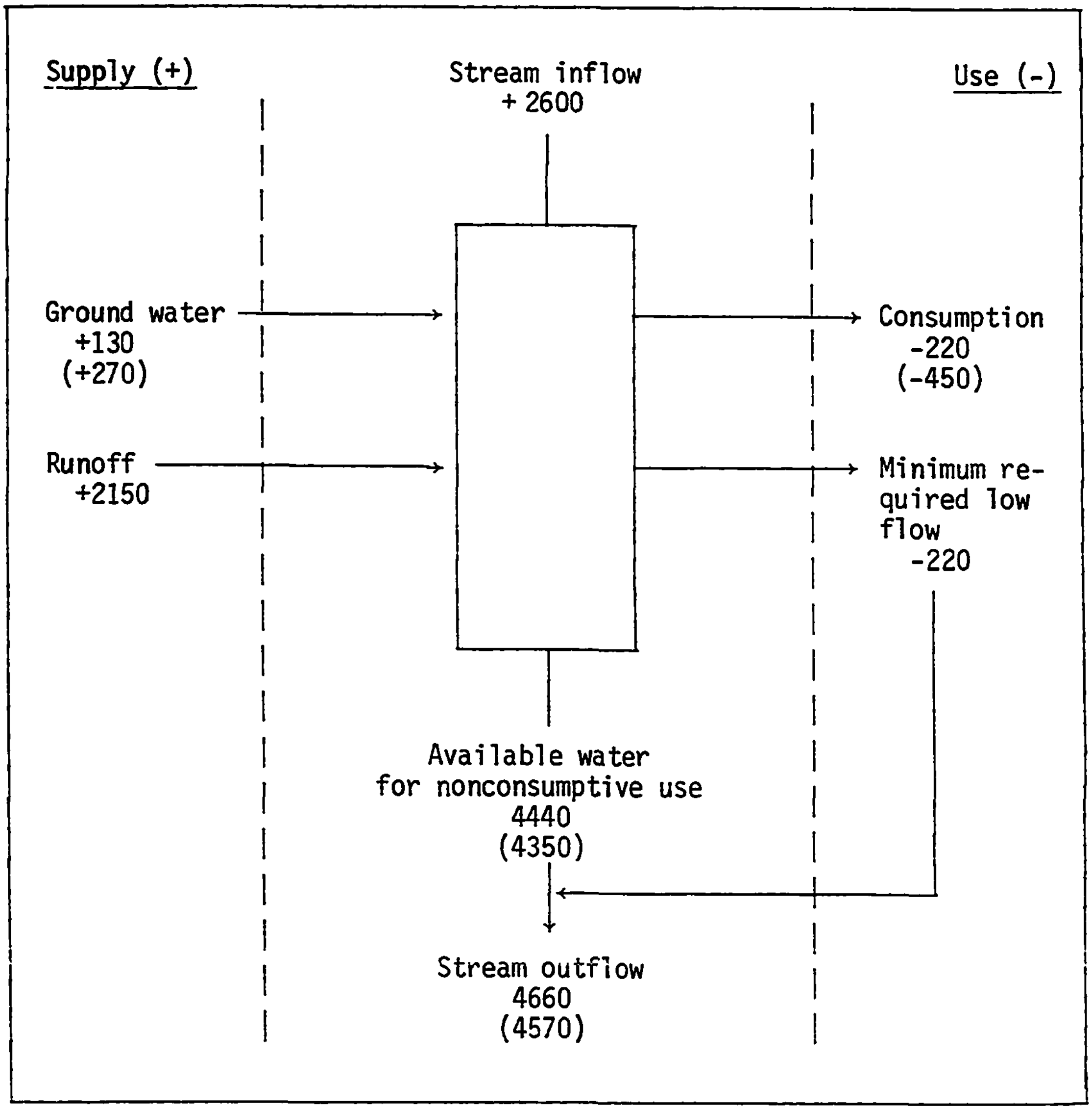


Figure 26. Water availability model for irrigation of low water-holding capacity soils in Central Iowa when a system of reservoirs is in operation; volumes in million cubic meters

The historical data show the source of about 60 percent of this water is from ground water. The amount is about 270 million cubic meters. The annual runoff for this area is about 2150 million cubic meters and the annual stream inflow is about 2600 million cubic meters. The average discharge at a location on a stream defines the total water available from the stream at that point. The annual average discharge varies greatly from year to year and cannot be used individually in hydrological analysis, but the average discharge derived from a long period of record is a stable value. The flow of a stream during dry periods is usually inadequate to meet the minimum water requirements without the use of storage. Water stored during periods of high flow can be released to supplement low flows during these critical periods. Values shown in Figure 26 are average values. Numbers shown in the parentheses are for a dry period when withdrawals of water for irrigation are higher than average. The minimum required low flow of the streams is set aside and is about 220 million cubic meters. Although this amount stays in the stream, to insure minimum flow it is considered to be in the negative part of the model. The reason for putting the ground water in the positive side is because it contributes to the amount of water taken by irrigation and gives a relief to the stream storage.

Theoretically, it appears from this model that, at most, only about 9 percent of the volume of water running in the stream would be taken out if there is going to be irrigation. The water available for other uses that must be nonconsumptive is about 4440 million cubic meters. Adding the minimum protected low flow to this amount, the average stream outflow then would be 4660 million cubic meters, which is far above conservation limits. In dry years, there could be little or no consumptive or nonconsumptive use. It can be stated that irrigation of low water-holding capacity soils in Central Iowa is possible if an appropriate water resources plan was in operation for this area in particular, and the state in general. Without this, dry years could impose a problem for surface water use. In reviewing the ground water resources, it was stated that if the water withdrawals are not going to be made from the surficial aquifers, but instead from a deeper aquifer, such as the Jordan, there does not seem to be a drawdown problem. The deep aquifer of the area can support the 270 million cubic meters annual withdrawal. The ground water storage under this area is about 20.9 to 86.4 billion cubic meters, with an annual recharge of 500 to 5000 million cubic meters, which prevents a sharp drawdown, except possibly in a very dry year when little recharge might take place. However, the use (450 million cubic meters) is a small percentage of the total available.

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APPENDIX

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C      REVISED SOIL MOISTURE PROGRAM      JUNE 1981       OLYA ARJMAND
C CAUTION:  ERRORS WILL OCCUR IF SILKING DATE IS 20 DAYS BEFORE
C OR 13 DAYS AFTER JULY 31.
C      TABLES AND CONSTANTS MAY NOT ACCURATELY REFLECT TRUE CONDITIONS,
C      ALTHOUGH PROGRAM WILL RUN AS LONG AS SILKING DATE IS IN JULY OR
C      AUGUST.
C ARRAYS USED:
C R(11,56)            RUNOFF TABLE
C ETS(120)            EVAPOTRANS / PAN EVAP TABLE
C SM1(3,101)          RELATIVE TRANSPIRATION  BEFORE AUG 1
C SM2(3,101)                 DITTO             AUG 1 & AFTER
C EXT(12,65)          ROOT EXTRACTION SCHEDULE
C FC(10)              FIELD CAPACITY, IN. / 6 IN.
C SAT(10)            SATURATION, IN. / 6 IN.
C SMP(10)             SOIL MOISTURE, IN. / 6 IN.
C COL(10)             AMOUNT TO BE EXTRACTED FROM EACH LAYER
C EXTR(10)            DIFFERENCE BETWEEN NEEDED & PRESENT MOISTURE
C BOT (10)            FIELD CAPACITIES ACCUMULATED TO EACH LAYER
C D(10)               DIFFERENCE BETWEEN EXTR(1) & AVAILABLE MOISTURE
C WTFAC(17)           STRESS WEIGHTING FACTOR TABLE
C AVECR(17)           VECTOR TO HOLD 5-DAY SUMS  OF RAW STRESS INDEX
C AVECW(17)           VECTOR TO HOLD 5-DAY SUMS OF WEIGHTED STRESS INDEX
C PERIOD(2)           VECTOR TO HOLD BEFORE AND AFTER HEADINGS
      DIMENSION R(11,56),ETS(120),SM1(3,101),SM2(3,101),EXT(12,65),P(5),
     1FC(10),SAT(10),SMP(10),COL(10),EXTR(10),D(10),BOT(10),
     3WTFAC(17),PERIOD(2),SUB(10),
     4AVECR(17),AVECW(17),IPMO(34),IPDAY(34)
   21 WRITE(6,22)
   22 FORMAT(1H1,10X,64H PROGRAM TO PREDICT SOIL MOISTURE UNDER CORN,
     2REVISION I-FELCH)
C
C     PROCEDURE TO READ IN TABLES USED IN COMPUTATIONS
C
      MONTH=1
      KRT=1
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```
      RTR=0.0
      IDTE=-999
C     READ IN R-THE RUNOFF TABLE
      READ (5,20) R
   20 FORMAT(11F2.1)
C     READ IN ETS(120)-ET/EVAP PAN RATIOS
      READ(5,80) ETS
   80 FORMAT(40F2.2)
C     READ IN SM1-RELATIVE TS PRIOR TO AUG 1
      READ (5,120) SM1
  120 FORMAT(3F3.2)
C     READ IN SM2-RELATIVE TS AFTER AUGUST 1
      READ (5,120) SM2
C     READ IN EXT-EXTRACTION PROFILES
      READ (5,290) EXT
  290 FORMAT(2X,F2.1,10F3.3,F2.0)
C     READ IN WTFAC - STRESS WEIGHTING FACTORS
      READ(5,295) WTFAC
  295 FORMAT(17F3.2)
C     READ IN PERIOD - B AND A (BEFORE AND AFTER)
      READ(5,296) PERIOD
  296 FORMAT(2A1)
C     ********************************************************************
C     END OF STAGE 1 .... ALL TABLES HAVE BEEN STORED
C
C     BEGINNING OF STAGE 2 .....RUNS THE COMPUTATIONS UP TO AND
C     INCLUDING JUNE 7
C
C     IDEN IS STATION IDENTIFICATION NUMBER
C     IDATE1 IS STARTING DATE FOR ANTECEDENT MOISTURE
C     IDATE2 IS MONTH FOR ENDING RUN
C     IDATE3 IS DAY FOR ENDING RUN
C     A ROUTINE TO READ IN INITIAL CONTROL CARDS FOR YEAR'S RUN,
C     RECORD INITIAL 5 DAYS PRECIPITATION AMOUNTS, COMPUTE STARTING
C     PER CENT AVAILABLE, READ (MAIN), CHANGE DATES TO NUMERICAL
```

```
C       FORM (ADJUSTED BY SILK DATE), COMPUTE RUNOFF AND NET PRECIP.,
C       EXTRACT FROM PROFILE VIA EXTRACTION SCHEDULE, AND ADD IN NET
C       PRECIPITATION.
  340 READ(5,7760,END=25)IDEN,IDATE1,IDATE2,IDATE3
 7760 FORMAT(I8,1X,I4,2X,I2,I2)
      IF (IDEN.NE.99999999) GO TO 7990
 7991 WRITE(6,79)
   79 FORMAT('1','  IDENTIFICATION NUMBER NOT FOUND.PROGRAM TERMINATED')
      GO TO 25
C       READ IN THE NUMBER OF ACTIVE LAYERS.
 7990 READ (5,361) LAYERS
  361 FORMAT(I2)
C       READ IN FC, SAT, AND INITIAL SMP BY 6" INCREMENTS.
      READ(5,350) FC
      READ(5,350) SAT
      READ(5,350) SMP
  350 FORMAT(10F3.2)
C       SUM FC INTO BOT(I) FOR USE AS DENOMINATOR LATER
      BOT(1)=FC(1)
      DO 355 I=2,10
      BOT(I)=BOT(I-1)+FC(I)
  355 CONTINUE
C       READ IN THE TOTAL PORESPACE FOR EACH OF THE TWO LAYERS
      READ (5,360) TPS1,TPS2
360   FORMAT(2F3.2)
C       READ IN SILKING DATE (MONTH-DAY) FOR THE YEAR.
      READ (5,370)MO,IDY
  370 FORMAT(4X,2I2)
C       PRINT OUT NUMBER OF ACTIVE LAYERS, FIELD CAPACITIES,
C       SAT VALUES, INITIAL PROFILE, AND SILKING DATE
C       FOR IDENTIFICATION OF RUN.
      WRITE (6,369) LAYERS
  369 FORMAT('1THERE ARE',I3,'  ACTIVE LAYERS.')
      WRITE(6,371) FC
  371 FORMAT(064H1FIELD CAPACITY    1    2    3    4    5    6    7    8
```

```
     1     9     10,/,/,/16X,10F5.2,/,/)
      WRITE(6,372) SAT
  372 FORMAT(064H SATURATION        1      2      3      4      5      6      7      8
     1     9     10,/,/,/16X,10F5.2,/,/)
      WRITE(6,373) SMP
  373 FORMAT(064H INITIAL PROFILE  1      2      3      4      5      6      7      8
     1     9     10,/,/,16X,10F5.2,/,/)
374   FORMAT (024H TOTAL POROSITIES 1     2,/,/,/16X,2F5.2,/,/)
      WRITE(6,374) TPS1,TPS2
      WRITE(6,375) MO,IDY
  375 FORMAT(010H SILK DATE,/,2X,I4,4X,I4)
      DO 378 I=1,17
      AVECR(I)=0.0
      AVECW(I)=0.0
  378 CONTINUE
      PCPN=0.0
      PERC=0.0
      IMOIS=0.0
      RAWSTR=0.0
      LKL=1
      III=0
      LML=1
      RNF=0.0
C     CONVERTS SILKING DATE FROM (MONTH-DAY) TO NUMERICAL FORM.
C     STOPS IF SILKING DATE IS NOT IN JULY OR AUGUST.
      IF(MO .NE. 7) GO TO 390
  380 MON=122
      GO TO 420
  390 IF(MO .NE. 8) GO TO 410
  400 MON=153
      GO TO 420
  410 WRITE(6,41)
   41 FORMAT('1', '  RECORDED SILKING DATE NOT IN JULY OR AUGUST, PROGRA
     1M TERMINATED')
      GO TO 25
```

```
C       CONVERTS NUMERICAL SILK DATE TO AN INTEGER (NSA) DEPENDING
C       ON NUMBER OF DAYS BEFORE OR AFTER AVERAGE SILKING DATE (JULY 31).
  420   NSA=153-(MON+IDY)
        IPOINT=0
C       IPRDTE IS THE STARTING DATE FOR THE 85 DAY PERIOD SURROUNDING
C       THE SILKING DATE
        IPRDTE=(MON+IDY)-39
C
C       READ IN P(5) VECTOR INITIAL PRECIPITATION AMOUNTS,
C       STATION I.D. # , AND TEST DATE.
C       READS THROUGH CARDS IF BEFORE STARTING DATE
C       Q IS TEMPORARY STORAGE OF P(I)
  431   READ(5,432)IDEN,ITEST1,Q
  432   FORMAT(I8,I4,10X,F4.2)
        IF (ITEST1.EQ.IDATE1) GO TO 7764
        IF (IDEN.NE.99999999) GO TO 431
        WRITE (6,7643) IDATE1
 7643   FORMAT( '1' / '0BEGINNING DATE - '   ,I4, ' - NOT FOUND' /'1' /'1')
        GO TO 340
C       BEGINNING DATE FOUND.
 7764   IRD=5
        KL=0
  435   P(IRD)=Q
        IF (IRD.EQ.1) GO TO 430
        READ(5,7762)ITEST1,Q
 7762   FORMAT(8X,I4,10X,F4.2)
        IRD=IRD-1
        GO TO 435
C       KRT1 IS INTEGER GIVING LOWEST LAYER NO. TO WHICH ROOTS
C       STMT# 430 STARTS A NEW DAY
  430   IF (IPOINT.EQ.1) GO TO 7751
C       IPOINT=1 IF AT ENDING DATE; IDATE3 & IDATE3
C       CONTINUE READING THROUGH IF THEY GO BEYOND THIS MONTH AND DAY
C       READ IN IDENTIFICATION, MONTH, DAY, PRECIP.& PAN EVAPORATION.
        READ (5,440) IDEN,IMO,IDAY,PCP,EVP
```

```
  440 FORMAT(I8,2I2,10X,F4.2,40X,F3.2)
C
C      REINITIALIZE THE DAILY PERC VARIABLE.
       DYPERC=0.0
C
C      TEST FOR ENDING DATE
C
       IF(IDEN.EQ.99999999) GO TO 340
       IF(IDAY.NE.IDATE3) GO TO 445
       IF(IMO.NE.IDATE2) GO TO 445
C      IPOINT=1 IF ENDING DATE IS FOUND
       IPOINT=1
       GO TO 445
C
C      BRANCHES HERE FROM STMT# 430
 7751  READ(5,7754)IDEN
 7754  FORMAT(I8)
C      A CARD OF 9'S SIGNIFIES START TO NEW YEAR'S COMPUTATIONS.
       IF(IDEN-99999999)7751,340,7751
C      WHENEVER MONTH IS NOT EQUAL TO MONTH ON CARD BEING READ, A
C      HEADER IS PRINTED OUT AT TOP OF NEW PAGE AND MONTH
C      IS RESET TO NEW MONTH.
  445  IF (MONTH.EQ.IMO) GO TO 550
 2001  WRITE (6,2002) IDEN,IMO
 2002  FORMAT (1H1,'IDEN=',I8,5X,'IMO=',I2//133H0DAY  PCP  EVP  ET   EVAP
      1 STET  RNF  1    2    3    4    5    6    7    8    9    10   TOT
      2 IPAV IPAV1 RTR RAWSTR PERC ATN1 ATN2 ATNV)
 2004  MONTH=IMO
C      ROUTINE TO ADD NET PRECIP. INTO PROFILE FILLING UP EACH LAYER
       GO TO (541,541,442,444,450,470,490,510,530,542,502,541), IMO
  442  M=0
       GO TO 550
  444  M=31
       GO TO 550
  450  M=61
```

```
      GO TO 550
  470 M=92
      GO TO 550
  490 M=122
      GO TO 550
  510 M=153
      GO TO 550
  530 M=184
      GO TO 550
  542 M=214
      GO TO 550
  502 M=245
      GO TO 550
  541 STOP
C     IDTE IS THE SUM OF NUMERICAL SEASONAL ADVANCE (DUE TO AVG. SILK
C     DATE) THEREMERICAL MONTH + DAY IN MONTH.
C     IDTE IS DATE ADJUSTED FOR SEASONAL ADVANCE
C     IDTEC IS CALENDAR DAY
  550 IDTEP=IDTE
      IDTEC=M+IDAY
      IDTE=NSA+IDTEC
      IF(IDTEP.EQ.IDTE-1) GO TO 551
      IF(KL.EQ.1) WRITE(6,552) IMO,IDAY
  552 FORMAT (' ','DATE PRECEDING  ',I2,'/',I2,'  IS MISSING')
C     KL SET TO 1 FOR REST OF YEAR'S RUN.
C     WILL PASS HERE ON FIRST DAY IDTE IS CALCULATED AND AT ALL OTHER
C     TIMES WHEN DAYS ARE OUT OF ORDER
      KL=1
  551 IF (IDTE.LE.99) GO TO 560
      IF(IDTE .LE.214) GO TO 571
C     KKK=-1 IF(IDTE.LE.99) IS TRUE
C     KKK=0 IF(100.LE.IDTE.AND.IDTE .LE.213) IS TRUE
C     KKK=1 IF(IDTE .GT.214) IS TRUE
C
      KKK=1
```

```
      GO TO 573
C     TO STAGE 4
  571 KKK=0
      GO TO 575
C     TO STAGE 3
C     *******************************************************************
  560 KKK=-1
      IPAV=(SMP(1)/BOT(1))*100.0 +0.5
      IF (IPAV .GT. 100) IPAV=100
      IPAV1=((SMP(1)+SMP(2))/BOT(2))*100.0 +0.5
      IF (IPAV1 .GT. 100) IPAV1=100
      IF(SMP(1) .GE. 0.10) GO TO 590
  580 EVAP=SMP(1)
C     IF THERE IS < 0.1" MOISTURE IN TOP 6" SET IT = 0.
      SMP(1)=0.0
      GO TO 600
C     IF THERE IS > OR = 0.1" IN TOP 6" , SUBTRACT 0.1" FROM IT.
  590 SMP(1)=SMP(1)-0.10
      EVAP=0.1
C
C START OF PORTION TO COMPUTE API, INTERPOLATE IN RUNOFF TABLE &
C COMPUTE NET PCP, I.E., PCPN
C     SKIP API CALCULATION ANS INFILTRATION IF NO PCP
  600 IF (PCP.LE.0.0001) GO TO 710
C I.E., NO NEED TO INFILTRATE
C
      IF(PCP.GT.0.5) GC TO 615
      PCPN=PCP
      GO TO 700
C I.E., NO NEED TO CORRECT FOR RNF
C RUNOFF CORRECTION FOLLOWS
  615 API=P(1)+P(2)/2.0+P(3)/3.0+P(4)/4.0+P(5)/5.0
      PPP=PCP
      IF(PPP.GT.6.0) PPP=5.99999
      IF(PPP.LT.1.0.OR.IDTE.GT.184) GO TO 650
```

```
      API=API+PPP*0.5
C  CONVERTS PPP TO SUBSCRIPT FOR RUNOFF TABLE
  650 IS1=(PPP*10.0)-3.5
      IF(API.LE.5.0) GO TO 651
      RNF=R(11,IS1)
      GO TO 681
C CONVERTS API TO SUBSCRIPT FOR RUNOFF TABLE
  651 L=(API*10.0)+0.5
      K1=API
      K2=K1*10
      K3=L-K2
      IF(K3.GE.5) GO TO 670
      LAP1=K2
      GO TO 680
  670 LAP1=K2+5
  680 IS2=LAP1/5 +1
      IS3=IS2+1
      RF1=R(IS2,IS1)
      RNF=(((L-LAP1)/5.0)*(R(IS3,IS1)-RF1))+RF1
C
C PCPN = PCP - RUNOFF (INTERPOLATED FROM TABLE)
  681 PCPN=PCP-RNF
C     NN IS COUNTER FOR LAYER NO.
C
  700 DO 790 NN=1,10
      DIF=FC(NN)-SMP(NN)
      IF(PCPN.GE.DIF) GO TO 789
      SMP(NN)=SMP(NN)+PCPN
      PCPN=0.0
      GO TO 710
  789 SMP(NN)=FC(NN)
      PCPN=PCPN-DIF
  790 CONTINUE
      DYPERC=PCPN
      PERC=PERC+PCPN
```

```
      IF(PERC.GT.0) GO TO 1
C     EXCESS MOISTURE ABOVE FIELD CAPACITY GRADUALLY FILLED EACH LAYER
C     UP TO SATURATION,STARTING FROM THE LOWEST LAYER,THEN FILLING
C     EACH LAYER UNTIL THE FIRST LAYER REACHED SATURATION.
1     SMP(LAYERS)=SMP(LAYERS)+PERC
      I=LAYERS
      DO 2 MM=1,LAYERS
      DIFFER=SMP(I)-SAT(I)
      IF(DIFFER.GE.0) GO TO 3
      PERC=0
      GO TO 710
3     SMP(I)=SAT(I)
      PERC=0
      I=LAYERS-MM
      IF(I.LE.0) GO TO 710
      SMP(I)=SMP(I)+DIFFER
2     CONTINUE
C     TO STAGE 5
      GO TO 710
C     *********************************************************************
C     STAGE 4 .....STEADY EVAPORATION-  0.35*PAN EVAP IF BEFORE
C     OCTOBER 31;  0.02" IF AFTER
C     ROUTINE TO COMPUTE AND EXTRACT THE AMOUNT OF EVAPORATION.
  573 IPAV=(SMP(1)/BOT(1))*100.0 +0.5
      IF (IPAV .GT. 100) IPAV=100
      IPAV1=((SMP(1)+SMP(2))/BOT(2))*100.0 +0.5
      IF (IPAV1 .GT. 100) IPAV1=100
      IF (IDTEC.LE.245) GO TO 1573
C     FOR MOST CONDITIONS PROGRAM SHOULD NOT GO BEYOND OCTOBER 31 (245)
      EVAP=0.02
      GO TO 1575
 1573 EVAP=0.35*EVP
 1575 IF (SMP(1).GE.EVAP) GO TO 576
      SMP(1)=0.0
      GO TO 600
```

```
C      SUBTRACT EVAP FROM TOP 6".
  576 SMP(1)=SMP(1)-EVAP
      GO TO 600
C      STMT # 600 RETURNS TO SEGMENT WHICH COMPUTES API AND RNF AND
C      THEN INFILTRATES PCPN
C      ***************************************************************
C      BEGINNING OF STAGE 3 ..... A ROUTINE TO HANDLE COMPUTATION OF
C      EVAPOTRANSPIRATION AND LAYER EXTRACTION PROCESS AFTER JUNE 7
C      ROUTINE COMPUTES AMOUNT OF ET (FROM ETS TABLE) AND THE STRESSED
C      ET (FROM THE SM1 OR SM2 TABLE) DUE TO THE PROPER STRESS
C      DEMAND CONDITIONS.
  575 ET=EVP*ETS(IDTE-99)
      IF(EVP.LT.0.3) GO TO 810
  800 IST=1
      GO TO 880
  810 IF(EVP.LT.0.2) GO TO 831
      IST=2
      GO TO 880
  831 IST=3
C
C      SEGMENT TO CALCULATE IARG
  880 IF (IDTE.GT.214) GO TO 5002
C      I.E.,PAST SEPTEMBER 30
      IF (IDTE.GT.99) GO TO 5003
C      I.E., PAST JUNE 7  (BUT NOT PAST SEPTEMBER 30)
 5002 IARG=65
      GO TO 1030
 5003 IF (IDTE.LT.148) GO TO 950
      IF(IDTE.LT.155) GO TO 1040
 1050 IARG=64
      GO TO 1030
  950 IARG=IDTE-98
      GO TO 1030
 1040 IARG=IDTE-91
C      KL=0 THE DAY BEFORE SMP OBSERVATION- NO EXTRACTION ON THIS DAY;
```

```
C     THEREAFTER KL=1
 1030 CONTINUE
C     ROUTINE TO EXTRACT FROM THE PROFILE VIA EXTRACTION SCHEDULE
C     PERCENTAGES OF THE AMOUNT OF STRESSED ET,I.E..STET
C     LL IS COUNTER FOR LAYER NO.
C     COL(10) IS A VECTOR WHERE AMOUNTS TO BE EXTRACTED FROM  EACH
C     LAYER (1-10) HAVE BEEN COMPUTED BY MULTIPLYING THE STRESSED ET
C     (STET) BY EXTRACTION PROFILES.
      KRT1=EXT(1,IARG)/0.5+0.0001
C     IPAV IS PER CENT AVAILABLE IN ACTUAL ROOT ZONE.
C     IPAV1 IS PER CENT AVAILABLE IN TOP FOOT.
      TOP=0.0
      DO 1033 I=1,KRT1
      TOP=TOP+SMP(I)
 1033 CONTINUE
      IPAV=(TOP/BOT(KRT1))*100.0+0.5
      IF (IPAV .GT. 100) IPAV=100
      IPAV1= ((SMP(1)+SMP(2))/BOT(2))*100.0+0.5
      IF (IPAV1 .GT. 100) IPAV1=100
      IF(IDTE.GE.154) GO TO 860
      RTR=SM1(IST,IPAV+1)
      GO TO 870
  860 RTR=SM2(IST,IPAV+1)
  870 STET=RTR*ET
      DO 3010 LL=2,11
      COL(LL-1)=STET*EXT(LL,IARG)
 3010 CONTINUE
C  EXTRACTION FROM LAYERS 3 & 4 IF 1 & 2 ARE BARE
      KRT=EXT(12,IARG)+0.001
C     KRT IS LAST LAYER OF ACTIVE ROOT ZONE.
      IF(SMP(1).LE.0.0) GO TO 3040
 3030 IF(SMP(2).GT.0.0) GO TO 3050
      COL(1)=COL(1)+COL(2)
      COL(2)=0.0
      GO TO 3050
```

```
 3040 IF(SMP(2).LE.0.0) GO TO 3070
      COL(2)=COL(1)+COL(2)
      CCL(1)=0.0
      GO TO 3050
 3070 EXTR(1)=0.0
      EXTR(2)=0.0
      IF(KRT.GT.2) GO TO 3090
      ADD=0.0
      GO TO 1160
 3090 LW=1
 3120 IF(SMP(LW+2).GE.COL(LW)) GO TO 3140
 3130 EXTR(LW+2)=COL(LW)-SMP(LW+2)
      SMP(LW+2)=0.0
      GO TO 3150
 3140 SMP(LW+2)=SMP(LW+2)-COL(LW)
      EXTR(LW+2)=0.0
 3150 IF(LW.EQ.(KRT-2)) GO TO 3170
      LW=LW+1
      GO TO 3120
 3170 ADD=COL(KRT-1)+CCL(KRT)
      GO TO 1160
C  REMOVES FULL AMOUNT OR MAX AVAILABLE FROM LAYERS 1 & 2
 3050 IF(SMP(1).GE.COL(1)) GO TO 3190
 3180 EXTR(1)=COL(1)-SMP(1)
      SMP(1)=0.0
      GO TO 3200
 3190 SMP(1)=SMP(1)-COL(1)
      EXTR(1)=0.0
 3200 IF(SMP(2).GE.COL(2)) GO TO 3220
      EXTR(2)=COL(2)-SMP(2)
      SMP(2)=0.0
      GO TO 3230
 3220 EXTR(2)=0.0
      SMP(2)=SMP(2)-COL(2)
C  SHIFT AMOUNT FROM 1 TO 2 & REMOVE EXTR, OR REVERSE
```

```
 3230 IF(EXTR(1).LE.0.0) GO TO 3250
 3240 IF(EXTR(2)) 3260,3270,3260
 3250 IF(EXTR(2)) 3280,3260,3280
 3270 IF(SMP(2).GE.EXTR(1)) GO TO 3300
 3290 EXTR(1)=EXTR(1)-SMP(2)
      SMP(2)=0.0
      GO TO 3260
 3300 SMP(2)=SMP(2)-EXTR(1)
      EXTR(1)=0.0
      GO TO 3260
 3280 IF(SMP(1).GE.EXTR(2)) GO TO 3320
 3310 EXTR(2)=EXTR(2)-SMP(1)
      SMP(1)=0.0
      GO TO 3260
 3320 SMP(1)=SMP(1)-EXTR(2)
      EXTR(2)=0.0
C     IF ACTIVE ROOT ZONE EXTENDS NO FURTHER THAN 2 LAYERS GO TO 3330.
 3260 IF(KRT.EQ.2) GO TO 3330
C  REMOVES AMOUNTS FROM BELOW LAYER 2
 3340 DO 3390 LN=3,KRT
      IF(SMP(LN).LT.COL(LN)) GO TO 3370
 3360 EXTR(LN)=0.0
      SMP(LN)=SMP(LN)-COL(LN)
      GO TO 3390
 3370 EXTR(LN)=COL(LN)-SMP(LN)
      SMP(LN)=0.0
 3390 CONTINUE
 3330 ADD=0.0
C     CNT COUNTS # OF LAYERS WHICH CONTAIN MOISTURE AND ARE IN
C     ACTIVE ROOT ZONE.
C     LP IS COUNTER FOR ACTIVE ROOT LAYERS.
C     TOT SUMS UP ALL EXTRA AMTS. TO BE EXTRACTED IN EXTR(10).
 1160 CNT=0.0
      TOT=0.0
      DO 1260 LP=1,KRT
```

```
 1230 IF(SMP(LP).LE.0.0) GO TO 1250
 1240 CNT=CNT+1.0
 1250 TOT=TOT+EXTR(LP)
      EXTR(LP)=0.0
 1260 CONTINUE
 1270 TOT=TOT+ADD
      IF(TOT.LE.0.0) GO TO 875
C
      IF (CNT.LE.0.0) GO TO 601
      TOTCNT=TOT/CNT
C     DIVIDE TOT BY CNT AND SUBTRACT THIS AMT. FRCM EACH OF THE
C     ACTIVE LAYERS STILL CONTAINING MOISTURE. ANY LEFTOVER AND
C     NOT YET EXTRACTED IS PUT IN VECTOR D(10).
C      LX IS COUNTER FOR ACTIVE ROOT LAYERS.
      DO 1290 LX=1,KRT
      IF(SMP(LX).GT.0.0) GO TO 1300
      D(LX)=0.0
      GO TO 1290
 1300 IF(SMP(LX).GE.TOTCNT) GO TO 1320
      D(LX)=TOTCNT-SMP(LX)
      SMP(LX)=0.0
      GO TO 1290
 1320 SMP(LX)=SMP(LX)-TOTCNT
      D(LX)=0.0
 1290 CONTINUE
C     CNT1 COUNTS THE NO. OF ACTIVE LAYERS WHICH STILL CONTAIN MOISTURE
C     TOT1 SUMS AMTS. PRESENT IN D(10) VECTOR.
C     LY IS CCUNTER FOR ACTIVE LAYERS.
 1340 CNT1=0.0
      TOT1=0.0
      DO 1390 LY=1,KRT
      IF(SMP(LY).LE.0.0) GO TO 1360
 1370 CNT1=CNT1+1.0
 1360 TOT1=TOT1+D(LY)
 1390 CONTINUE
```

```
C       LZ IS ACTIVE ROOT LAYER COUNTER.
        IF(TOT1.LE.0.0) GO TO 875
        IF(CNT1.LE.0.0) GO TO 601
        TTCNT1=TOT1/CNT1
        DO 1415 LZ=1,KRT
        IF(SMP(LZ).LE.0.0) GO TO 1415
  1410  IF(SMP(LZ).GE.TTCNT1) GO TO 1440
        SMP(LZ)=0.0
        GO TO 1415
  1440  SMP(LZ)=SMP(LZ)-TTCNT1
  1415  CONTINUE
C   REMOVE  H2O FROM LAYER 1 IF ET.GT.STET & H2O IS PRESENT
C       IF THERE IS STILL MOISTURE IN TOP LAYER AND THE DIFFERENCE
C       BETWEEN ET AND STRESSED ET IS < OR = TO 0.1 THEN AN ADDITIONAL
C       AMT. CAN BE EXTRACTED FROM THE TOP LAYER UP TO THE DIFFERENCE
C       (ET-STET) OR EQUAL TO 0.1 IF ET-STET > 0.1.
   875  EVAP=0.0
        ETSTET=ET-STET
        IF(ETSTET.GT.0.1) GO TO 910
        IF(SMP(1).GE.ETSTET) GO TO 930
   920  EVAP=SMP(1)
        SMP(1)=0.0
        GO TO 601
   930  SMP(1)=SMP(1)-ETSTET
        EVAP=ETSTET
        GO TO 601
   910  IF(SMP(1).LT.0.1) GO TO 920
   940  SMP(1)=SMP(1)-0.1
        EVAP=0.1
C       RAWSTR IS CALCULATED IN THREE WAYS DEPENDING ON THE VALUES OF EVP,
C       STET, AND EVAP.  IF STET < OR = .04 AND EVP > .30, THEN
C       RAWSTR=1-STET/ET.  OTHERWISE RAWSTR=1-(STET+EVAP)/ET, WHERE THE
C       MAXIMUM ALLOWABLE VALUE FOR EVAP IS .05
   601  IF(ET.LE.0.0) GO TO 645
        GO TO 646
```

```
  645 RAWSTR=0.0
      GO TO 642
  646 IF(EVP.GT.0.30.AND.STET.LE.0.04) GO TO 640
      GO TO 641
  640 RAWSTR=1-(STET/ET)
      GO TO 642
  641 IF(EVAP.GE.0.05) GO TO 643
      GO TO 644
  643 RAWSTR=1-(STET+.05)/ET
      GO TO 642
  644 RAWSTR=1-(STET+EVAP)/ET
  642 CONTINUE
C     AT THIS POINT WE ENTER INTO STAGE TWO TO COMPUTE RUNOFF AND
      GO TO 600
C
C**********************************************************************
C     STAGE 5....SEGMENT TO WRITE OUTPUT AND REINITIATE
C     ATOT SUMS MOISTURE IN WHOLE PROFILE.
C     ALSO COMPUTES WEIGHTED STRESS INDEXES
  710 ATOT=0.0
C     CALCULATE THE AVERAGE AERATION AS A PERCENTAGE OF THE TOTAL
C     SOIL VOLUM OF THE FIRST FOOT.
      IARTN1=((TPS1-SMP(1))/6)*100+0.5
      IARTN2=((TPS2-SMP(2))/6)*100+0.5
      IARNAV=(IARTN1+IARTN2)/2+0.5
C     QVANTIFY THE EXTENT OF EXCESS MOISTURE BETWEEN MAY 9 AND JULY 1.
      IF(IDTE.GE.71.AND.IDTE.LE.122) GO TO 591
      GO TO 1910
591   IF(IARNAV.LE.10)IMOIS=IMOIS+1
1910  CONTINUE
      DO 1911 JA=1,10
      ATOT=ATOT+SMP(JA)
 1911 CONTINUE
 1913 IF(KKK.EQ.0) GO TO 1740
      KET=0
```

```
      STET=0.0
      RTR=0.0
      GO TO 1750
 1740 KET=(100.0*ET)+0.5
 1750 CONTINUE
C
      IF(RAWSTR.LE.0.0) RAWSTR=0.0
      IF(IDTEC.GE.IPRDTE.AND.IDTEC.LE.IPRDTE+84)CALL SUM(AVECR,RAWSTR,
     1LKL,LML,III,IPMO,IPDAY,IMO,IDAY)
1751  WRITE(6,1800) IDAY,PCP,EVP,KET,EVAP,STET,RNF,SMP,ATOT,
     1IPAV,IPAV1,RTR,RAWSTR,DYPERC,IARTN1,IARTN2,IARNAV
1800  FORMAT(' ',I2,F6.2,F5.2,1X,I3,1X,F6.3,12F5.2,F6.2,2I5,1X,
     12F5.2,F6.2,3I5)
      PCPN=0.0
      RNF=0.0
      IF(IPOINT.EQ.1) GO TO 1808
C     REINSTATE BY MOVING UP ANTECEDENT PRECIPITATION AMOUNTS.
      P(5)=P(4)
      P(4)=P(3)
      P(3)=P(2)
      P(2)=P(1)
      P(1)=PCP
      GO TO 430
C     STMT # 430 STARTS A NEW DAY
 1808 CONTINUE
C     COMPUTE 5-DAY WEIGHTED STRESS INDEXES.  IN ADDITION, WHENEVER
C     RAW STRESS INDEX FOR TWO OR MORE CONSECUTIVE 5-DAY PERIODS IS
C     > OR= 4.50 MULTIPLY WEIGHTED INDEX BY 1.5
C     IN ADDITION, WHENEVER MORE THAT ONE OF 1B,2B,3B, HAVE A RAW STRESS
C     INDEX OF > OR = 3.0 MULTIPLY THOSE WEIGHTED INDEXES OF PERIODS 1B,
C     2B,3B WHICH ARE > OR = 3.0 BY 1.5
C     IN ADDITION, WHENEVER 1B AND 1A RAW STRESS INDEXES ARE > OR = 4.5,
C     DESIGNATE A CROP FAILURE
      IND=0
      DO 1630 IW=1,17
```

```
      AVECW(IW)=AVECR(IW)*WTFAC(IW)
      IF(IW.EQ.1)GO TO 1630
      IF(AVECR(IW).GE.4.50)GO TO 1631
      IND=0
      GO TO 1630
 1631 IF(AVECR(IW-1).GE.4.50)GO TO 1632
      GO TO 1630
 1632 IF(IND.NE.1)GO TO 1633
      AVECW(IW)=AVECW(IW)*1.5
      IND=1
      GO TO 1630
 1633 AVECW(IW-1)=AVECW(IW-1)*1.5
      AVECW(IW)=AVECW(IW)*1.5
      IND=1
 1630 CONTINUE
      KST=0
      LST=0
      MST=0
      IF(AVECR(6).GE.3.0)KST=1
      IF(AVECR(7).GE.3.0)LST=5
      IF(AVECR(8).GE.3.0)MST=10
      NST=KST+LST+MST
      IF(NST.EQ.6)GO TO 1640
      IF(NST.EQ.11)GO TO 1641
      IF(NST.EQ.15)GO TO 1642
      IF(NST.EQ.16)GO TO 1643
      GO TO 1645
 1640 AVECW(6)=AVECW(6)*1.5
      AVECW(7)=AVECW(7)*1.5
      GO TO 1645
 1641 AVECW(6)=AVECW(6)*1.5
      AVECW(8)=AVECW(8)*1.5
      GO TO 1645
 1642 AVECW(7)=AVECW(7)*1.5
      AVECW(8)=AVECW(8)*1.5
```

```
      GO TO 1645
 1643 AVECW(6)=AVECW(6)*1.5
      AVECW(7)=AVECW(7)*1.5
      AVECW(8)=AVECW(8)*1.5
 1645 CONTINUE
      WRITE(6,1801) IDEN
 1801 FORMAT('1SUMMARY FOR STATION IDENTITY CODE  ',I8,/)
      WRITE(6,1806)
 1806 FORMAT('-',31X,'RAW STRESS',6X,'WEIGHTED STRESS')
      WRITE(6,1807)
 1807 FORMAT(' DATES',11X,'PERIOD',11X,'INDEX',14X,'INDEX'///)
      MNM=8
      NMM=1
      NB=1
      MK=0
      DO 1823 NMN=1,17
      WRITE(6,1805) IPMO(NMM),IPDAY(NMM),IPMO(NMM+1),IPDAY(NMM+1),MNM,
     1PERIOD(NB),AVECR(NMN),AVECW(NMN)
      NMM=NMM+2
      IF(MK.EQ.1)GO TO 1850
      MNM=MNM-1
      GO TO 1851
 1850 MNM=MNM+1
      GO TO 1823
 1851 IF(MNM.EQ.0)GO TO 1852
      GO TO 1823
 1852 NB=2
      MNM=1
      MK=1
 1823 CONTINUE
 1805 FORMAT(' ',I2,'/',I2,'-',I2,'/',I2,7X,I1,A1,2F18.2)
C     CALCULATE WEIGHTED STRESS SUM FOR 85 DAY PERIOD
      WSTSUM=0.0
      DO 1655 IWR=1,17
      WSTSUM=WSTSUM+AVECW(IWR)
```

```
 1655 CONTINUE
      WRITE(6,1654) WSTSUM
 1654 FORMAT(' '///' 85-DAY WT. STRESS SUM',F10.2)
      WRITE (6,1658) IMOIS
1658  FORMAT(' NUMBER OF INADQUATE AERATION DAYS BEFORE JULY 1',I6)
      WRITE(6,1656) PERC
 1656 FORMAT(' SEASON PERCOLATION TOTAL',F7.2)
      IF(AVECR(8).GE.4.50.AND.AVECR(9).GE.4.50)GO TO 1652
      GO TO 430
 1652 WRITE(6,1650)
 1650 FORMAT('0THERE WAS SEVERE MOISTURE STRESS FIVE DAYS BEFORE AND ')
      WRITE(6,1651)
 1651 FORMAT(' FIVE DAYS AFTER SILKING, RESULTING IN A CROP FAILURE')
C     GO TO STMT# 430 AND READ THROUGH CARDS IF ANY
      GO TO 430
   25 STOP
      END
      SUBROUTINE SUM(AVECR,RAWSTR,LKL,LML,III,IPMO,IPDAY,IMO,IDAY)
      DIMENSION AVECR(17),IPMO(34),IPDAY(34)
C     THIS SUBROUTINE SUMS THE RAWSTR VALUES INTO 5-DAY PERIODS SUCH
C     THAT 8 PERIODS FALL BEFORE THE SILKING DATE AND 9 PERIODS FALL
C     AFTER THE SILKING DATE.
      AVECR(LML)=AVECR(LML)+RAWSTR
      III=III+1
      IF(III.EQ.1)GO TO 1860
      GO TO 1861
 1860 IPMO(LKL)=IMO
      IPDAY(LKL)=IDAY
      GO TO 1865
 1861 IF(III.EQ.5)GO TO 1862
      GO TO 1865
 1862 LKL=LKL+1
      LML=LML+1
      IPMO(LKL)=IMO
      IPDAY(LKL)=IDAY
```

```
      LKL=LKL+1
      III=0
 1865 RETURN
      END
$ENTRY
```